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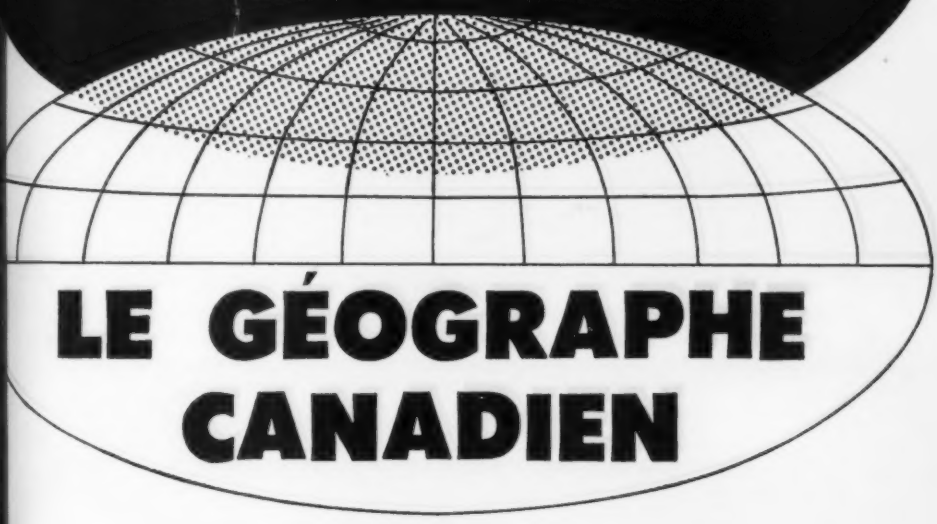

LE GÉOGRAPHE CANADIEN

L'ASSOCIATION CANADIENNE DES GÉOGRAPHES

Number 16
July 1960

THE CANADIAN ASSOCIATION OF GEOGRAPHERS
L'ASSOCIATION CANADIENNE DES GEOGRAPHES

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THE CANADIAN GEOGRAPHER
LE GEOGRAPHE CANADIEN

NO. 16, JULY, 1960

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THE CIRCULATION OF THE ARCTIC*

ROY LEE

Meteorological Service of Canada

BEFORE TRYING to present a review of recent research on the general circulation of the Arctic, it is necessary to discuss in some detail the meaning of this expression. In any attempt to give a systematic and consistent picture of a general subject, it is important to keep the basic questions in mind and proceed to discuss the observed facts in the light of physical principles. The basic question to be considered here is the description and explanation of the large-scale (time and space) behaviour of the Arctic atmosphere, i.e., atmospheric flow patterns having physical dimensions of the continents and of the earth itself. The approach taken is to describe the observed mean large-scale behaviour of the Arctic atmosphere in the light of four fundamental physical factors: namely, differential solar heating, the rotation of the earth, the location of mountain barriers and the geostrophic thermal wind equation.

The physical features of the Arctic regions may be briefly described as follows. The polar cap consists mainly of the Arctic Ocean which is almost completely land-locked except for one main access to the warmer waters of the Atlantic between Greenland and Norway. The central Arctic basin is covered with a permanent ice pack which extends to the continents during the winter. The land masses in the Arctic are Siberia, Alaska, northern Canada and Greenland. These land masses are far from uniform in elevation, rather, there are large mountain barriers along the east coast of Asia and in western North America. Finally, the warm waters of the Pacific and Atlantic Oceans extend to high latitudes.

It is desirable to examine the mean large-scale air motions in the Arctic against this background of land, sea and mountains. A model of the circulation of the atmosphere in meridional planes is shown in Figure 1. This is a schematic diagram presented by Rossby in 1941[10] showing the classical three-cell structure of the atmospheric circulation. (It should be noted that this model has not gained universal acceptance among meteorologists.) The area of interest here is the northernmost of these three cells, in which there is considered to be general descending motion near the pole, a surface easterly circulation in the polar cap and a westerly circulation aloft. The purpose of this schematic picture was to describe in very general terms the planetary meridional circulation averaged with respect to latitude and time; hence, one must not infer that the daily wind patterns will necessarily conform to this picture. The magnitudes of the vertical movements are in general too small to be detectable from daily observations; nevertheless, on the planetary scale, this model would appear to have general degree of validity.

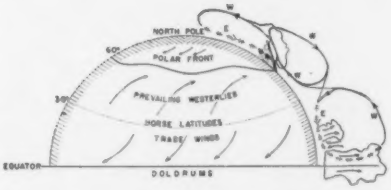

FIG. 1. The final cellular meridional circulation on a rotating earth: Convection near the equator, a clear zone of descending air motion north of it (about latitude 30° N.), and heavy slanting cloud masses with accompanying precipitation in the polar-front zone (55°–60° N). (After Rossby.)

THE MEAN SEA LEVEL PRESSURE DISTRIBUTION

One can examine the mean sea level pressure distribution to see how the actual mean surface wind field compares with this schematic picture described by Rossby. The normal pattern of the mean sea level circulation is well established by the work of many authors including Baur,[1] U.S. Weather Bureau[12] and more recently by

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Namias[7] who showed eight-year averages of mean sea level pressure and 700-mb height over the Arctic for January, April, July and October.

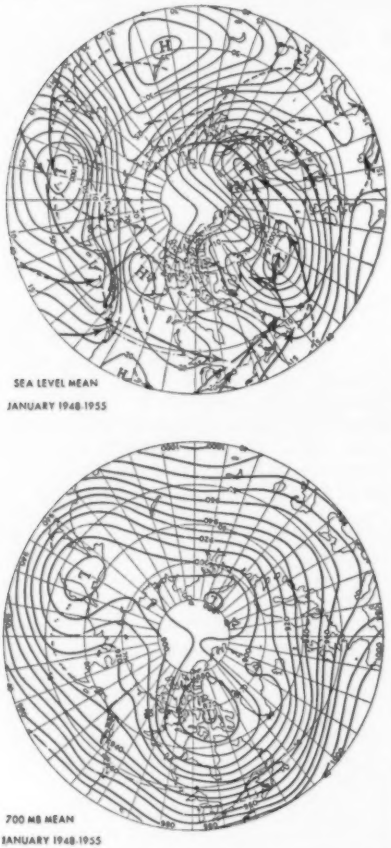


FIG. 2. 'Normal' distribution of sea-level pressure and 700-mb height for January. (After Namias, Trans. Amer. Geophys. Union.)

The January mean sea level chart is shown in Figure 2, from which one can observe immediately that there is not a mean surface easterly flow throughout the polar cap as one might be led to infer from Rossby's schematic diagram; rather, there is a distinctly cellular pattern in the wind field with large mean cyclones over the warm oceans and large anticyclones over the cold continents. Mean surface easterly winds occur only to the north of the oceanic low pressure cells. There is, moreover, a marked asymmetry in the wind field insofar as the belt of mean easterlies north of the Icelandic low extends beyond the pole. The centre of circulation appears to lie along the 180° meridian and has been called by La Seur the circulation pole. An average of the surface wind around latitude circles centred with respect to the circulation pole would permit one to infer the existence of the net polar easterly circulation which Rossby showed in his diagram.

One might be led to inquire if there is a rational basis for the existence of a cellular structure in the mean sea level circulation or for the precise location of the Icelandic and Aleutian lows and Siberian high. The discussion of the cellular structure will be deferred for a moment in order to consider the results of a theoretical investigation by Smagorinsky.[11] He investigated the relation between the location of these pressure features and the location of the heat sources and sinks in the northern hemisphere and showed on theoretical grounds that mean surface low pressure cells should occur about 25 degrees of longitude east of the heat sources and that mean surface high pressure cells should occur about 25 degrees of longitude east of the cold sources. Referring to the January mean sea level map, it is observed that the Icelandic low is found approximately this distance east of the region of maximum heating due to the warm ocean off the North American coast and the latent heat of condensation in the belt of maximum precipitation just inland. In the far western Pacific the position of maximum precipitation coincides with that of the maximum heating from the warm Kuroshio current. The Aleutian low appears to have the correct location with respect to these heat sources. The Siberian high pressure cell may be considered to be generated by the cold source some 25 to 30 degrees of longitude to the west of it, as inferred from mean surface isotherms and isobars.

Other features of the January mean sea level chart are a ridge of high pressure extending across northern Alaska connect-

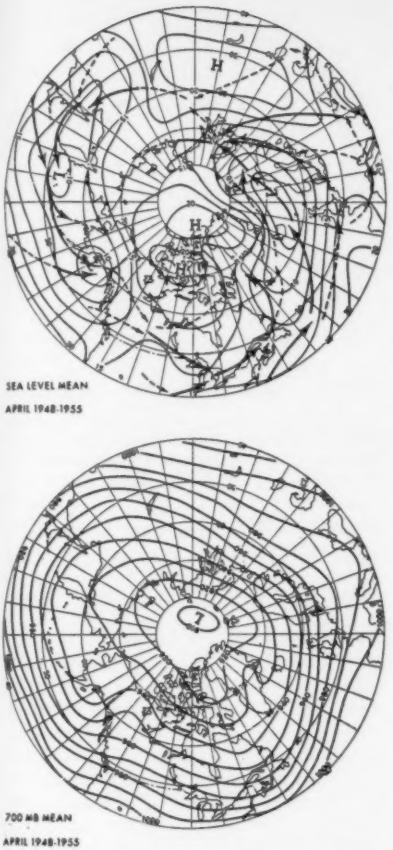


FIG. 3. 'Normal' distribution of sea-level pressure and 700-mb height for April. (After Namias, Trans. Amer. Geophys. Union.)

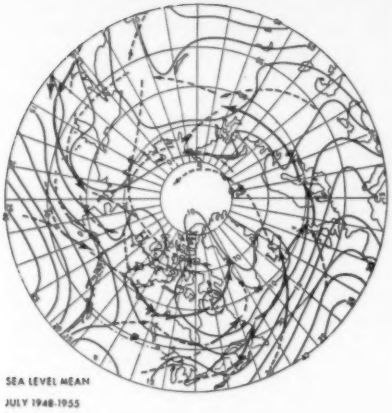
ing the continental high pressure cells. Finally, there are mean troughs of low pressure extending from the Aleutian low toward the Gulf of Alaska and from the Icelandic low along the coast of Norway and the U.S.S.R. One can infer from the mean January chart that anticyclones frequently develop in the Alaskan area. These anticyclones are associated with masses of cold Arctic air which sweep southward in the wake of depressions of the more southerly latitudes. The mean troughs of low pressure in the Gulf of Alaska and along the northern coast of the U.S.S.R. suggest belts of frequent cyclonic activity, verification for which can be found in the locations of the storm tracks in Figure 2. The principal storm track occurs along the oceanic fringe of Norway and the U.S.S.R. and spirals in toward the North Pole. The occurrence of cyclonic activity in the vicinity of the pole was confirmed by weather records from the Russian expedition "North Pole" in 1937–39. For example, on one occasion a 24-hour temperature change of 52°F accompanied by a pressure change of 1 inch of mercury was reported. Secondary storm tracks occur across Bering Strait, along the Arctic coast of Canada and northward from Labrador through Davis Strait to Baffin Bay.

Figure 3 illustrates the mean sea level pressure in April which shows marked changes in the general circulation from January, the most noticeable of which is the relaxation in pressure gradient. This relaxation can be attributed to the weakening of the heat sources along the coastlines as the temperature difference from land to ocean diminishes with the season. At the same time, the character of the Arctic basin sea-level circulation becomes more anticyclonic so that the mean pressure there is some 3–4 mb higher than in January.

The July mean sea level map in Figure 4 shows a relatively flat pressure field in the Arctic. This is largely due to the highly variable pressures during this season, when weak cyclones and anticyclones occur very frequently. Evidence for cyclonic activity in the basin itself in the summertime is shown by the secondary storm tracks which exhibit a tendency to spiral in toward the North Pole. The mean low pressure centre in the Gulf of Alaska vanishes from spring to summer probably owing to the lack of temperature difference between Alaska and the Pacific Ocean in July. The main belts of cyclonic activity shift south from winter to summer especially in the European Russian sector.

THE UPPER TROPOSPHERIC CIRCULATION

Before discussing the upper tropospheric circulation, it is of interest to consider the temperature distribution at high latitudes and its relationship to the wind field.



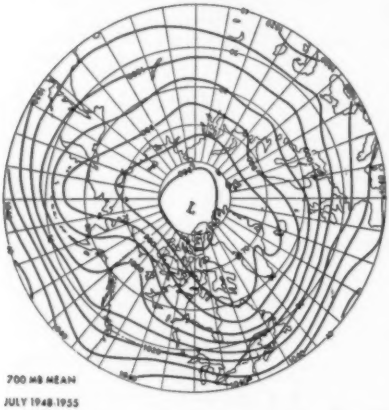


FIG. 4. 'Normal' distribution of sea-level pressure and 700-mb height for July. (After Namias, Trans. Amer. Geophys. Union.)

Clearly, the shape of the earth is one factor controlling the temperature and its daily and seasonal variations. Since the earth is nearly spherical, the net solar radiation per unit area of the surface varies with latitude which should theoretically result in isotherms coinciding with latitude lines. However, the presence of warm oceans at high latitudes introduces an asymmetry into the surface temperature field. Consequently, the pattern of mean isotherms is distorted to conform more or less to the shape of the coast-lines as shown in Figure 5. This

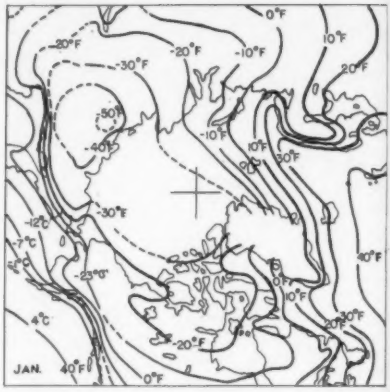


FIG. 5. Approximate distribution (ignoring complications due to relief) of mean daily temperature for January. (After Hare and Orvig, McGill Univ.)

mean sea level isotherm pattern persists to higher altitudes. The significance of this thermal pattern is that it yields the variation of wind with height expressed quantitatively by the geostrophic thermal wind equation. The meaning of this equation can be described as follows. Suppose the horizontal wind at the base of an atmospheric layer is represented by a directed line segment or vector with length proportional to the wind speed (V_1). If the orientation and horizontal spacing of the mean isotherms in that layer are known, then one can visualize a thermal wind vector (V_T) parallel to the mean isotherms whose magnitude is inversely proportional to the distance between isotherms. The wind at the top of the layer (V_2) will then be found by the rule of vector addition shown in Figure 6.

Returning to the mean isotherm map for January, it is seen that colder air occurs toward the pole, consequently the thermal wind vector is generally directed from west to east. The strength of the easterly circulation should then gradually diminsh from the surface to higher levels and shift to westerly. A comparison of the flow at 700 mb (around 9,000 ft) with the mean sea level flow in Figure 2 will show this variation of wind with height, which is manifest in the belt of westerly winds around the

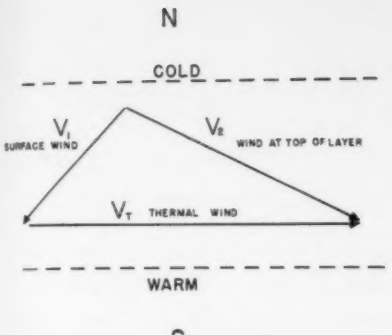


FIG. 6. Relationship between surface wind (V_1), wind at top of layer (V_2) and the mean isotherms in the layer.

hemisphere, often referred to as the circumpolar vortex. Another notable feature is that the mean westerly flow pattern is distinctly wave-shaped with three nearly symmetrical troughs and ridges around the hemisphere. In each case the troughs are located downstream from the main mountain barriers along the east coast of Asia and the Rockies.

A comparison of the January mean sea level map with the corresponding upper-level map will show that the main storm tracks are parallel to the upper flow with the main ones originating near the upper-level trough positions and ending near the upper-level ridge positions. This relationship is known as the principle of steering of surface cyclones by the upper flow.

The normal upper-air pattern in July shown in Figure 4 is somewhat similar to that in January with respect to the central Arctic vortex and the troughs near Kamchatka and eastern Canada. However, the flow is much weaker and one can detect evidence for the presence of four or possibly five waves. The number of waves is very closely related to the strength of the winds, in general, longer wavelengths are associated with stronger winds.

At this point, one is led to inquire: in what sense can we understand the existence of the circumpolar vortex, the large-scale train of waves which occurs in the westerly flow, and the cellular pattern of the surface wind field? Now, explanations in a physical science are characterized by one thing in common. An explanation of a phenomenon is said to be satisfactory if the phenomenon can be viewed as a logical consequence of established physical principles. For example, the motions of planets or the behaviour of moving objects are understood in so far as they can be deduced from the laws of classical mechanics expressed as Newton's laws of motion. In a similar manner one can speculate on the behaviour of a fluid on the rotating earth and ask: "What pattern of motion will a fluid exhibit under circumstances in which the physical factors can be controlled?" This problem has been treated theoretically but its complexities are such that a discussion of them is beyond the scope of this review. However, the same question may be asked from an experimental point of view. Such an approach has been followed at the University of Chicago by Riehl and Fultz.[9] Basically their experiment is arranged as shown schematically in Figure 7.

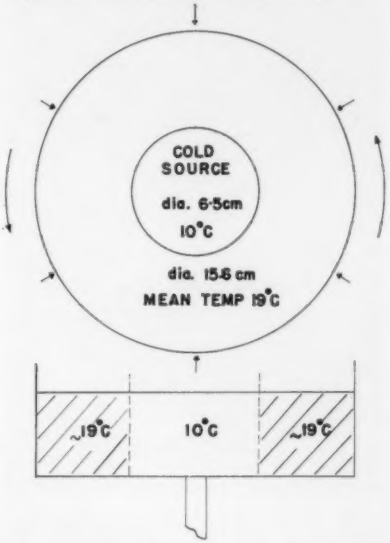


FIG. 7. Schematic diagram of dishpan experiment apparatus used by Riehl and Fultz, University of Chicago.

An ordinary circular vessel of about 16 cm radius, affectionately referred to as a dishpan, is filled with water to a depth of 4 cm and is supplied with a heat source

with a nominal intensity of 150 watts at the equatorial rim. A cylindrical cold source with a radius of 6.5 cm is centred at the pole and provides an analogy with the cold source in the Arctic. When heat is applied at the rim, the resulting circulation of the water occurs largely in meridional planes. However, when the dishpan is rotated in the same sense as the earth, the flow pattern becomes zonal. A steady state can be attained depending on the intensity of the heat source and the rate of rotation, factors which can be varied at will. Now by an ingenious photographic arrangement, a movie camera can record the movement of the water by photographing floating aluminum powder. Thus the fluid motion as it would be seen by an observer standing on the dishpan can be shown. The object of this is to simulate the observation of the atmosphere relative to the earth.

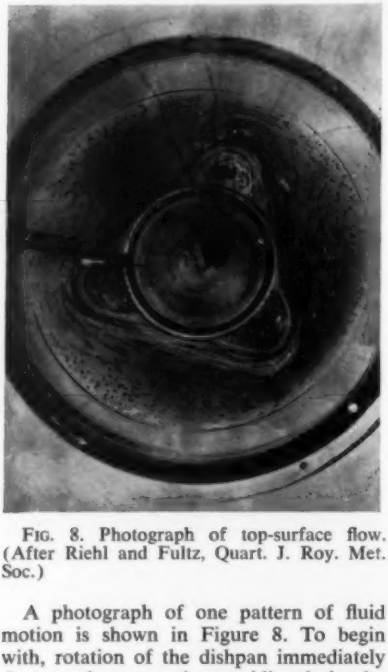


FIG. 8. Photograph of top-surface flow. (After Riehl and Fultz, Quart. J. Roy. Met. Soc.)

A photograph of one pattern of fluid motion is shown in Figure 8. To begin with, rotation of the dishpan immediately destroys the convective meridional circulation and establishes a strong westerly stream at the top surface in middle latitudes. Secondly, a Rossby wave pattern emerges and by altering the rate of rotation, the waves can be made stationary relative to the dishpan or can be made to propagate downstream, upstream or to change in number. To the north and south of the westerly current, the flow is sluggish but does exhibit a cellular pattern with cyclonic and anticyclonic eddies. Moreover, the original uniform horizontal temperature gradient is concentrated into a narrow zone in middle latitudes. Figure 9 shows the jet stream clearly as a broad band with a speed of 20 per cent of the equatorial speed, comparable to 200 miles per hour, extending almost uniformly along the jet axis. Cyclonic eddies occur to the north of the jet stream while anticyclonic eddies occur around latitude 30 degrees. In this particular situation, three waves occur in the pattern.

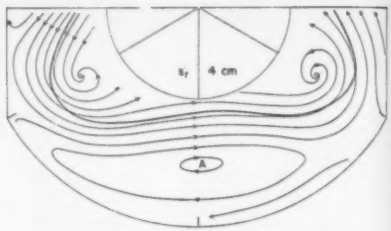


FIG. 9. Relative streamlines on top surface. Heavy solid line is jet-stream axis. (After Riehl and Fultz, Quart. J. Roy. Met. Soc.)

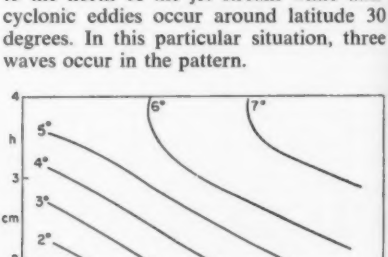


FIG. 10. Zonally-averaged distribution of temperature (departure from 16°C) with radius and height above bottom (cm). (After Riehl and Fultz, Quart. J. Roy. Met. Soc.)

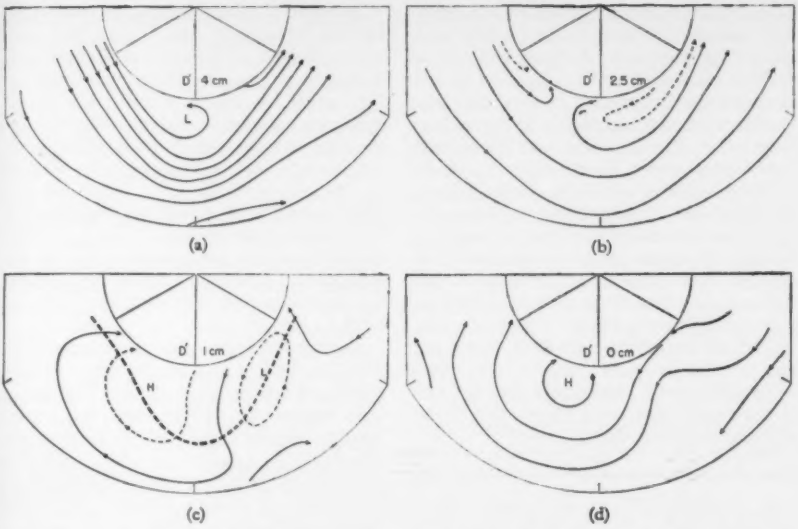


FIG. 11, (*a*), (*b*), (*c*) and (*d*): Contours on four selected isobaric surfaces (D') shown as stream function of geostrophic velocity. Double-dashed line at 1 cm is jet-stream axis at top surface (heights are indicated on diagrams). (After Riehl and Fultz, Quart. J. Roy. Met. Soc.)

The mean radial cross-section of temperature, given as departures from 16°C, is shown in Figure 10. It is obtained by averaging over all meridians and shows a strong north-south temperature gradient in middle latitudes which is strongest at the bottom and diminishes upward. This temperature field is again consistent with the wind field, as one can see by examining the calculated flow patterns at various levels in the dishpan shown in Figure 11. The jet stream decays downward and goes into a cellular pattern below 2 cm. A cyclone and an anticyclone are observed directly under the jet, with centres near the southwest and northwest inflection points of the upper current. This would be the analogue of the atmospheric sea level chart. The model also shows an easterly-westerly-easterly distribution of winds, comparable to that observed in the atmosphere when averaged zonally. On the bottom of the dishpan we find a sinusoidal easterly current, which would likely be obtained in the atmosphere in middle latitudes after downward extrapolation to about 5,000 ft below mean sea level.

Owing to the influence of the frictional boundary layer there were some winds at the bottom in the region just under and just ahead of the upper trough not indicated by this analysis. These were mainly northwesterly winds that occurred in a narrow sector behind a shallow cold front which appeared to lie on the average about ten degrees of longitude ahead of the upper trough. This front extended only slightly above 0.5 cm in height; evidence for its existence was given by much sharper breaks in the temperature traces when this feature moved past the temperature sensing element.

The significance of these experiments is that a replica of the atmospheric sea-level chart can be produced in the laboratory in association with an upper flow pattern which is related to it through the thermal wind equation.

A slightly different approach to the study of the general circulation was undertaken by Phillips[8] when he was at the Institute for Advanced Study in Princeton. This approach was made possible by the development of the modern electronic com-

puter. Whereas the properties of a rotating fluid subjected to heating and cooling were studied experimentally by Fultz and others, Phillips undertook an investigation of the same problem by means of an experiment based on recent experience in numerical forecasting. The problem was formulated thus: starting with an atmosphere initially at rest relative to a rotating earth which is subjected to differential heating, make a numerical forecast based on a simplified form of Newton's laws of motion. What type of flow pattern will develop in this atmosphere? At first the latitudinal heating and cooling should begin to create a mean latitudinal temperature gradient. After this has reached a certain critical value, large-scale eddies will presumably develop and it was hoped that some mean state of the atmosphere would finally evolve.

The results of the experiment were very striking. Figures 12 and 13 show the forecast 1,000-mb contours and 500-mb isotherms at 11 days and 26 days respectively. First of all, a cellular pattern develops at mean sea level which exhibits the easterly-westerly-easterly surface wind distribution. It is surmounted by an open wave pattern in the upper flow as revealed by the 500-mb isotherms. Again, a comparison of the 500-mb isotherms at 11 days and 26 days will reveal the intensification of the temperature gradient with time, or in effect, the development of a very strong jet stream aloft.

During the period from 5 days to about 23 to 27 days, a very regular wave pattern developed having many of the features of the large-scale eddies seen on actual weather charts. Individual waves were ob-

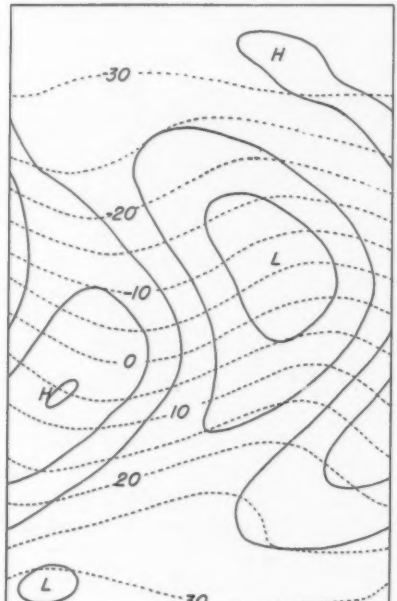


FIG. 12. Distribution of 1000-mb contour height at 200-foot intervals (solid lines) and 500-mb temperature at 5°C intervals (dashed lines) at 11 days. (After Phillips, Quart. J. Roy. Met. Soc.)

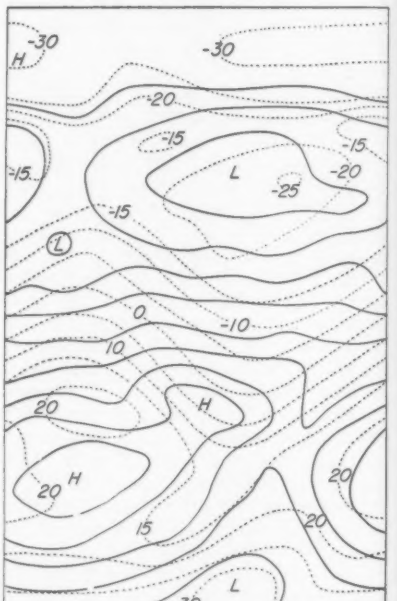


FIG. 13. Distribution of 1000-mb contour height at 200-foot intervals (solid lines) and 500-mb temperature at 5°C intervals (dashed lines) at 26 days. (After Phillips, Quart. J. Roy. Met. Soc.)

served to move eastward at about 1,800 km per day. These waves began as warm lows but a tongue of cold air gradually caught up with each deepening surface low centre and the tongue of warm air moved over the surface high centre so that in the final stages, the pattern looked very much like that of an occluded cyclone. The main surface troughs and ridges and also at upper levels were oriented so as to lean back toward the northwest in the northern half of the region and toward the southwest in the southern half of the region. Definite indications of something similar to cold and warm fronts are to be seen in the 1,000-mb contours (mean sea level) with the main temperature gradient occurring on the cold side of the frontal trough.

To recapitulate briefly then, these two investigations of fluid motion by H. Riehl, D. Fultz and N. A. Phillips in situations where the physical factors can be controlled, permit one to infer the following. A fluid on a rotating earth which is subjected to differential heating will develop an upper westerly flow around the pole in middle latitudes. In this westerly flow, an open wave pattern will appear and the waves will be distributed more or less symmetrically around the hemisphere. The individual troughs and ridges can occur anywhere on the earth, only their relative positions remain fixed. The effect of rotation is to intensify the existing temperature gradient into a very narrow zone, leading to the development of a jet stream at upper levels. At the surface, a cellular pattern of winds develops with a belt of high pressure around 30° latitude, south of which the winds are easterly, corresponding to the trades. Westerlies occur in middle latitudes with polar easterlies to the north. Features similar to low level fronts and cyclones also show up which are completely consistent with real atmospheric phenomena.

At this point one might ask why the individual upper troughs and ridges in the atmosphere take up such definite positions. Recalling that the major troughs occur just east of the Tibetan plateau and the Rockies which are separated by 120° longitude, it appears as though the orographic barriers determine the trough positions. It happens that these two barriers are separated by a distance corresponding to a wave number of 3. Thus the Kamchatka trough and Hudson Bay trough may be regarded as forced perturbations, a view that is supported by theoretical investigations. Indeed, one also observes on mean charts a lee trough east of the Andes in the southern hemisphere. The third trough in the Arctic occurs some 90 degrees downstream from Greenland, however, the strong westerlies are observed to pass south of Greenland so it appears that the icecap plays a relatively unimportant role in determining the positions of the large-scale planetary waves. The third trough near Novaya Zemlya can be considered to be a resonance wave induced by the other two perturbations.

THE STRATOSPHERIC CIRCULATION

The Arctic stratospheric circulation may now be examined in the light of these principles. Figure 14 illustrates the January

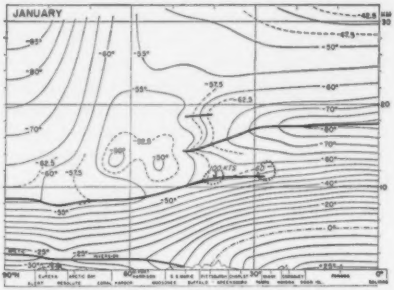


FIG. 14. Profile of mean temperature along 80°W in January. Isotherms in deg.C. (After Kochanski, J. Met.)

temperature field along the 80°W meridian as is shown by Kochanski.[5] In this the typical features of the Arctic tropospheric temperature field which is largely characterized by near homogeneity at high latitudes can be observed. However, above the tropopause, there is a very strong temperature contrast from south to north. The reason for its existence lies in the fact that the ozone layer is found around this level. Although it occurs in minute amounts, ozone is extremely sensitive to solar radiation—if it encounters sunlight, it warms up very quickly. Now, the geographical location of this zone of maximum temperature gradient suggests that it is likely due to

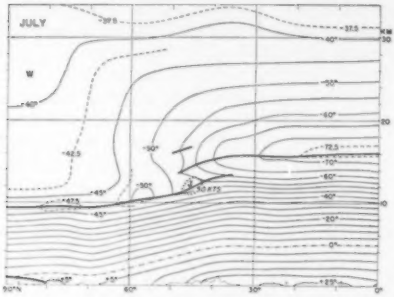


FIG. 15. Profile of mean temperature along 80°W in July. Isotherms in deg.C. (After Kochanski, J. Met.)

differential heating of the ozone layer along the earth's shadow cone. The fact that the Arctic stratosphere is appreciably warmer at the pole than at lower latitudes in July when the polar regions receive continuous sunlight lends support to this hypothesis (Figure 15). The existence of this horizontal temperature gradient through this deep layer during polar darkness should result in increasing westerly winds with height. The symmetry of the earth's shadow cone should lead us to expect a circumpolar vortex in the Arctic stratosphere with predominantly westerly winds. The effect of the earth's rotation is to intensify the existing horizontal temperature gradient. Furthermore, there will be a tendency to establish a Rossby wave pattern.

Figure 16 shows the mean January 25-mb contours (approximately 80,000 ft) over the North American sector. A mean trough will be observed in the vicinity of Hudson Bay which is similar to the tropospheric pattern. Figure 17 shows a vertical cross-section of the jet stream at 1500 GCT 20 November 1955. Stations selected for the cross-section are Eureka (917), Isachsen (074), Mould Bay (072), Sachs Harbour (051) and Norman Wells (043). The orientation of the cross-section is NE–SW so that the northwesterly winds at and above the 100-mb level (around 53,000 ft) are nearly at right angles to the plane of the cross-section. During November, the jet stream is in its initial stages of development and is therefore relatively weak. Nevertheless, the observations do define a wind speed maximum clearly in this cross-section. The temperature field around 65,000 ft is of particular interest. One can observe the greatest concentration

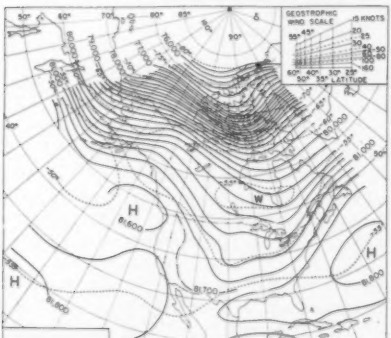


FIG. 16. 25-mb mean flow in January. Contours at 200-foot intervals (solid lines) isotherms in 5-deg. C. intervals (broken lines). (After Kochanski and Wasko, Bull. Amer. Met. Soc.)

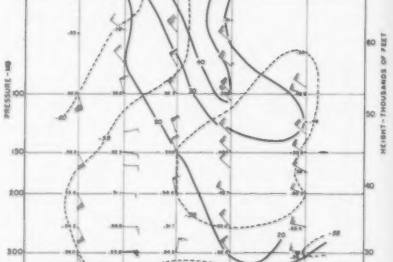


FIG. 17. Vertical cross section of Arctic Stratospheric Jet Stream 1500 GCT 20 November 1955. Orientation is approximately NE-SW. Tropopause is indicated by thick solid line, isotherms (C) by broken lines, and isotachs of observed northwesterly winds in stratosphere by thin solid lines (kn). (After Lee and Godson, J. Met.)

of isotherms between Sachs Harbour (051) and Isachsen (074); farther south, the horizontal temperature gradient is quite small.

A vertical cross-section through the jet stream at 1500 GCT 26 February 1956 is shown in Figure 18. It was around this time of the 1955–56 winter that the jet stream was most intense. The orientation of this cross-section is also NE–SW and the strong northwesterly winds in the stratosphere are again nearly at right angles to the plane of the cross-section. The highest reported wind on this cross-section is 160 kt around the 80,000-ft level at Eureka (917). The strong horizontal temperature gradient below the jet stream is clearly evident; the temperature decreases from —70°C to —50°C in a distance of 800 miles. Owing to the orientation and irregularity of the cross-section, there is some doubt as to the reality of the double maximum.

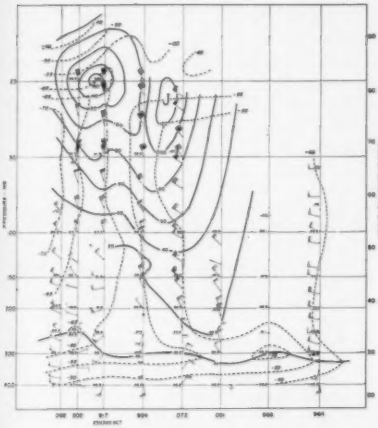


FIG. 18. Vertical cross-section of Arctic Stratospheric Jet Stream 1500 GCT 26 February 1956. Tropopause is indicated by thick solid line, isotherms (C) by broken lines, and isotachs of observed northwesterly winds in stratosphere by thin solid lines (kn). (After Lee and Godson, J. Met.)

A vertical cross-section for 0300 GCT 26 March 1956 is presented in Figure 19. The maximum wind occurs at or above the 80,000-ft level over Isachsen (074) with a speed of around 120 kt. It is also noted that

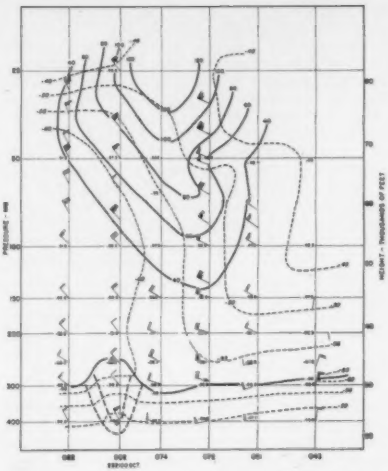


FIG. 19. Vertical cross section of Arctic Stratospheric Jet Stream 0300 GCT 26 March 1956. Tropopause and frontal surfaces are indicated by thick solid and broken lines, respectively, isotherms (C) are indicated by broken lines, and isotachs of northwesterly flow in stratosphere by thin solid lines (kn). (After Lee and Godson, J. Met.)

a maximum wind was reported in the Alert sounding at 75,000 ft indicating that the actual height of the jet axis is very nearly there on this occasion. The horizontal temperature gradient at 50,000 ft is 10°C over a distance of 860 miles, certainly much less than in the February cross-section where the maximum horizontal temperature gradient was estimated to be 20°C in 800 miles. The highest reported wind on this cross-section was slightly greater than 100 kt at 80,000 ft.

Consider now another planetary scale phenomenon, namely the ocean circulation, and ask if the general principles discussed above are not manifest in the ocean as well. The phenomenon in question is the Gulf Stream. It is well known that the Gulf Stream is a narrow, relatively fast-moving current off the east coast of North America. Figure 20 shows a vertical cross-section of the Gulf Stream off Chesapeake Bay. The lines of equal speed of the current are indicated by solid lines in cm per second. The dashed lines are isotherms in °C.

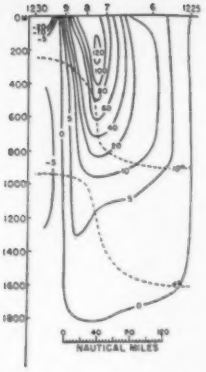


FIG 20. Relation between temperature distribution and current distribution in Gulf Stream off Chesapeake Bay. Isotherms are given by broken lines, lines of equal current velocity (in centimetres per second) by full lines. (After Staff Members, Dept. of Meteor., U. of Chicago; Bull. Amer. Met. Soc.)

It will be noted that there is a definite core of maximum speeds similar to the jet streams in the atmosphere. The greatest vertical increase in speed with height occurs in association with the thermocline, or the region where the isothermal surfaces are steepest. Finally, the current is extremely narrow, again possibly due to the intensification of the horizontal temperature gradient by the earth's rotation. Comparison of the slope of isotherms with those in the dishpan experiment will reveal a striking similarity.

SUMMARY

To sum up, it is apparent that the January surface wind circulation in the Arctic is in no sense characterized by a general easterly current over the polar cap, but rather that the sea-level circulation exhibits a cellular structure. The cells of high and low are consistently located with respect to the heat sources and sinks. The surface wind field is surmounted by a circumpolar vortex within which there are on the average three long waves or Rossby waves in the winter, with two of the troughs located east of the Tibetan Plateau and the Rockies and the third near Novaya Zemlya. On the basis of the dishpan experiments, it may be inferred that differential heating of a fluid on a rotating earth is sufficient to demonstrate the development of a cellular structure in the surface circulation and the intensification of the existing temperature gradient into an upper narrow jet stream in middle latitudes. A Rossby wave pattern arises as a natural consequence of the motion. Similar features occur in the stratosphere. The temperature gradient which arises from differential solar heating of the ozone layer along the edge of the earth's shadow cone is intensified by the earth's rotation resulting in a strong westerly current in which a basic 3-wave Rossby pattern also develops. The ridges and troughs in this wave pattern are consistently located with respect to the main mountain barriers. Finally, the Gulf Stream structure manifests a narrow jet core within which the maximum vertical rate of increase in water speed is associated with the thermocline. The experimental and observational phenomena considered here appear to be quite dissimilar, nevertheless, viewed in the light of four physical factors, namely, differential solar heating, the rotation of the earth, the presence of mountain barriers and the geostrophic thermal wind equation, one observes a sense of physical unity.

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RÉSUMÉ

Le but premier de l'auteur est de décrire et d'expliquer les phénomènes d'ensemble (dans le temps et l'espace) de la circulation atmosphérique des régions arctiques. La distribution des pressions moyennes au niveau de la mer, la circulation en haute troposphère et les mouvements stratosphériques sont décrits brièvement. Deux expériences bien distinctes permettent de démontrer l'existence d'un système cellulaire: la première, conduite par Riehl et Fultz, simule les mouvements atmosphériques par rapport à la terre, et la seconde, celle de Phillips, consiste dans la computation électronique des mêmes phénomènes basée sur des prévisions quantitatives obtenues récemment par expérimentation.

L'examen des résultats de ces deux expériences permet de conclure que la circulation des vents de surface dans l'Arctique en Janvier n'est nullement caractérisée par un courant d'Est dominant la calotte polaire, mais que la circulation au niveau de la mer possède une structure cellulaire. Les cellules de haute et de basse pression sont toujours distribuées en fonction des sources de chaleur et des zones de divergence. L'aire des vents de surface est surmontée d'un vortex circumpolaire qui comprend en moyenne trois longues vagues (Rossby waves) en hiver, deux des fossés se trouvant à l'Est du Plateau Tibétain et des Montagnes Rocheuses et le troisième près de la Nouvelle-Zemble. L'expérience de Riehl et Fultz permet de conclure que le réchauffement différentiel d'un fluide sur un globe en rotation suffit à démontrer le développement d'une structure cellulaire dans la circulation de surface et la conversion du gradient thermique existant en un étroit courant-fusée à haute altitude au-dessus des latitudes moyennes. Un système de vagues (Rossby waves) résulte naturellement de ce mouvement.

Des phénomènes semblables ont lieu dans la stratosphère. Le gradient thermique qui découle du réchauffement différentiel solaire de la couche d'ozone sur le rebord du cône d'ombre terrestre devient plus accentué par suite de la rotation de la terre et produit un fort courant d'Ouest où domine également un système de trois vagues (Rossby waves). Les crêtes et les fossés sont toujours situés en fonction des barrières montagneuses.

Un autre phénomène à l'échelle planétaire, i.e. les courant océaniques, obéit aux mêmes principes que le courant-fusée stratosphérique. La structure du Gulf Stream, par exemple, comprend un courant-fusée central où le taux maximum d'augmentation de la vitesse est en rapport avec le gradient thermique. Les phénomènes d'observation et d'expérimentation dont il est ici question semblent très différents; néanmoins, lorsqu'on les considère à la lumière de quatre facteurs physiques, i.e. le réchauffement différentiel solaire, la rotation de la terre, la présence de barrières montagneuses et l'équation des vents thermiques géostrophiques, on saisit le sens de l'unité physique.

THE LIMESTONE PAVEMENTS OF NORTHWESTERN ENGLAND*

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McGill University

As long ago as 1893 Cvijic recognized lapiés and pavemented surfaces as features peculiar to limestone terrain.[1] Several detailed studies by his contemporary, E. Chaix, demonstrated the widespread development of these superficial features in the Alps,[2] and there followed several papers discussing their origin, which were critically examined by Eckert in 1902[3] and Helpert in 1907.[4] The first publication in English to discuss this problem was that of Cvijic in 1924,[5] and this has remained a classic treatment up to the present day. Contemporary interest in the surface landforms of limestone areas is largely restricted to French and German geomorphologists, the outstanding contribution being that of Corbel.[6]

In the northwest of England where the Carboniferous Limestone outcrops over extensive areas around Morecambe Bay and in the Ingleborough district of west Yorkshire, bare limestone pavements have long been recognized as a distinct feature of the terrain (Figure 1), and local dialect words

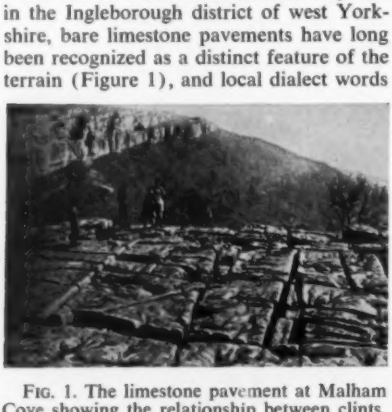

Fig. 1. The limestone pavement at Malham Cove showing the relationship between clints, grykes and scars. (Photo by H. A. Moisley.)

with a precise connotation have come into being to describe them. Thus, the word 'clint' refers to the bare flat-topped blocks of limestone, which are separated from each other by a network of weirdly shaped fissures known as 'grykes.' The pavements formed by the clint surfaces vary from a few yards to several hundred yards in width, and are generally fairly level. They may be either horizontal, or have a gentle slope corresponding to the angle of the dip of the beds on which they are formed. When traversing the scarp slopes of the moorlands, one passes across an irregular staircase—the outcrops of the beds with their pavemented surfaces forming the treads, and the risers resulting from the outcrop of the next overlying bed, each forming a minor scarp, known locally as a 'scar', along the hillside. The pavements are in fact a series of bedding planes from which the overlying strata have been locally removed to a greater or lesser extent. This relationship to structure is readily apparent. Many of the early geologists make incidental reference to it, but without attempting any explanation of the processes removing the overlying beds, or the rate of removal.[7] A more recent paper by Moisley poses the problem more precisely.[8] In it he discusses the matter of structural control in some detail, but does not reach any conclusion as to the processes involved in the formation of either the pavements or the grykes. The present paper is presented as a further contribution to this problem, and is a review of the conclusions reached after a field study of the pavements in northwest England.

The Influence of Lithology

As can be seen from the generalized section (Figure 2), the Lower Carboniferous is made up of a series of limestones of varying purity, with fairly rapid changes from standard limestones to shaly limestones, sandy beds, dolomites, and pebble beds. In the main, it is on the standard limestones that the more extensive pavements are produced, but obviously the

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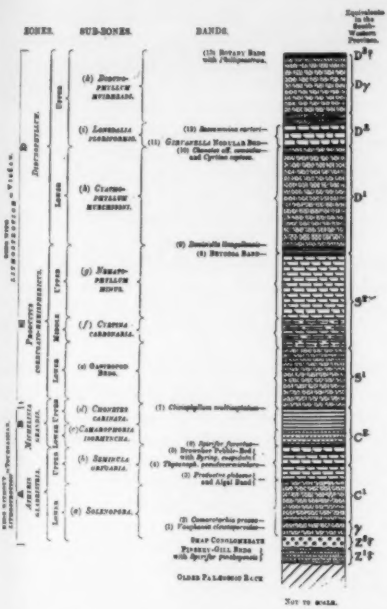
ZONES.
SUB-ZONES.
BANDS.
Equivalents in the Basalt-Andesite Province.
Dibunophyllum
Productus
Michelinia
Dibunophyllum-minus
Nematophyllum-minus
Cyrtina-carbonaria
Chonetes papilionacea
Seminula ornithica
Solenopora
Dibunophyllum-Zone
Productus-Zone
Cyrtina-carbonaria-Zone
Michelinia-Zone
Dibunophyllum-minus-Zone
Nematophyllum-minus-Zone
Cyrtina-carbonaria-Zone
Chonetes papilionacea-Zone
Seminula ornithica-Zone
Solenopora-Zone
Upper Limestone Group
Lower Limestone Group
Yoredale Series
Carboniferous Limestone Series
Dyne
Lower
Middle
Upper
Lower
Upper
Lower
Upper
Lower

organisms. Pavements are developed on almost all the beds of this sub-zone. Particularly extensive pavements are found on the so-called 'Spotted Beds,' which are characteristic of the base and the summit of the sub-zone; the 'Pseudo-Breccias,' which lie in the middle of the sub-zone; and the *Chonetes*-aff *comoides* and *Cyrtina-septosa* Band, which consists of a bed of very pure, platy, limestone, pale buff in colour, and some 2 to 3 feet thick (Figure 3).

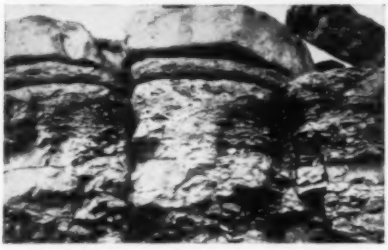

FIG. 3. The prominent scar formed by the *Cyrtina septosa* Band near the summit of Hampsfell. The purity and thickness of this band make it a persistent pavement-former. The 3-inch surveying aneroid on the lower beds indicates the scale.

The *Upper Dibunophyllum* sub-zone forms the passage beds between the Carboniferous Limestone and the Millstone Grits, and consists of alternations of limestones and sandstones, with some shaly material. In all there are about fifteen limestone beds in this group, but the majority are dark, impure, and either ferruginous or argillaceous. Only in a few cases do they give rise to well developed pavements.

The most apparent factor emerging from this review of the lithology of the Lower Carboniferous beds is the close relation between pavementation, and the purity and massiveness of the limestone beds. In general, it is the massive limestone beds, which in some cases have undergone slight metamorphism, that produce the most extensive pavements. Another factor of even greater significance is the existence of laminae which are chemically or physically more resistant than the overlying and underlying strata. In some instances, these laminae are bands of shale or argillaceous

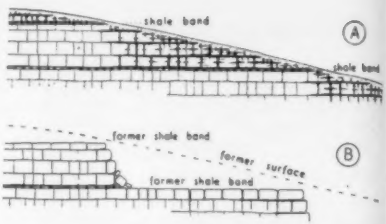

FIG. 4. Cross sections of a limestone pavement showing the bedding and indicating the manner in which the pavement is formed: A, after a long period of weathering; B, after removal of the debris. (After H. A. Moisley.)

material; more often they are limestone bands with more silica or dolomite than the adjacent beds. In the Great Scar Limestone such variations are very common, in spite of the apparent homogeneity of the beds. In Figure 4 the shale band is used to illustrate any such resistant stratum, and this structure provides the optimum conditions for pavementation. Percolation of surface water would dissect the exposed limestone outcrops above the shale bands, while the limestone beneath would be protected by this impermeable layer for some considerable time. It would only require some process to remove the overlying debris to create a perfect pavement surface. In many instances this type of structure is not immediately apparent on the pavements themselves, because the shale band has also been removed, but it can be demonstrated by investigating the sequence of the beds in sections down dip, which are still complete.

THE INFLUENCE OF STRUCTURE

The relationship of the pavements to the dip of the beds on which they are developed is another important factor. It was found that the inclination of the pavement surfaces was closely related to the dip of the rocks throughout the area. Around Morecambe Bay, the beds are dipping to the south and east at between 5° and 15°, and the pavements slope in corresponding directions, either forming the summits of hills and ridges, or as distinct scars where they outcrop on the scarp slopes, or long more irregular facets on the dip slopes. To the east, in the Pennines there is a change

in the direction of the dip to the east and northeast, and a reduction of the angle of dip to between 2° and 10°. The pavement surfaces correspondingly change their orientation and their inclination. However, throughout the area there is a tendency for the pavements to be less steeply inclined than the beds on which they are developed. In other words, the pavements represent erosional surfaces to some extent, so that the beds may have a dip of, for example, 15°, while the pavement developed along the outcrop of the beds dips at only 12°, showing the effects of subaerial processes in bevelling across the exposure.

The Grykes

Turning now to the grykes, it can be seen from Figure 5 that there are two types: first, a group of crevasse-like clefts, which are long, often gently curving, and vary in distance apart from a few feet to several tens of feet. They are often as much as 3 feet in depth, and can reach 6 feet; widths vary from several inches to a few feet, and they are best developed in thick beds of limestone (Figure 6). Secondly, there are a series of smaller, less regular furrows on the surface of the clints, which in some instances, as can be seen in Figure 5, have a rough dendritic pattern, in other cases, a parallel pattern, while in some rare examples, the furrow terminates in a minute swallow hole (Figure 7). The large furrows in the dendritic pattern can be up to six inches in depth, while the smaller tributaries are usually only an inch deep. Their direction is controlled by the slope of the clint surface, in the main they follow the line of maximum slope, starting close to the highest part of the block, traversing it, and terminating as minute hanging valleys in the next large gryke.

Fig. 5. The two types of grykes developed on a limestone pavement in the Ingleborough district. The 3-inch surveying aneroid indicates the scale.

Fig. 6. A deep crevasse-like gryke following the gently curved alignment of a shearing fracture near the Craven fault. The notebook indicates the scale.

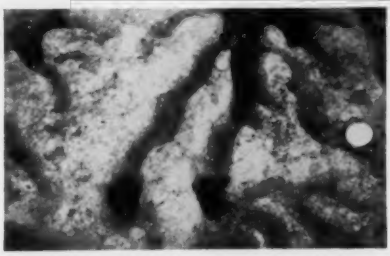

Fig. 7. Small grykes terminating in miniature swallow holes on a limestone pavement in the Morecambe Bay district. The 3-inch surveying aneroid indicates the scale.

The first set of grykes are solution-widened joints. This can be clearly demonstrated in many parts of northwest England by comparison of the gryke pattern with that of the jointing in adjacent non-limestone areas, and in those parts of the limestone where the joints have been cemented with calcite, galena and barytes.[10] The patterns are almost identical, and in some instances can be shown to merge with each other: as the degree of mineralization decreases, the gryking becomes correspondingly better developed. In the western Pennines the jointing is composed of two sets at right angles to each other, one set running northeast–southwest, the other, northwest–southeast. Further west, around Morecambe Bay, they change direction be-

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coming north–south, and east–west. Where both sets are strongly developed and close together the limestone is cut into rectangular blocks (Figure 8). Besides the major joints, there are also two other trends at 45° to them. These are not as well developed, but locally can be important, producing different gryke systems on the pavement surfaces. The deep grykes are developed in all instances from these joints which were produced initially as shearing fractures in the latter part of the Carboniferous or during the Permian, at the same time as the great boundary faults of Dent and Craven. The joints were probably reactivated in more recent times during the Eocene or the Miocene.

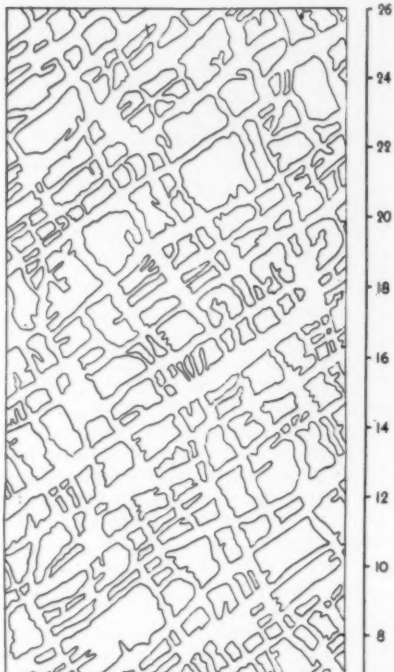

FIG. 8. Plan of 280 square yards of typical limestone pavement showing the gryke systems in Littondale. The scale is in yards and the plan is orientated north and south.

The alignment of the pavement edges is most commonly parallel to the strike of the beds. However, both dip and strike have been determined by the major lines of faulting which have produced a series of slightly tilted plateau blocks from an original horizontal sequence. The joints are genetically associated with this faulting, and so it is apparent that the pavement edges are, in fact, determined by the excavation of grykes along the joint systems which run parallel to the strike. The retreat of the pavement edges is thus in thin slabs: each clint block at the edge of the pavement is subject to sapping at the base by horizontal fissures, and by vertical fissures along the system of grykes which run parallel to the dip (Figure 9). The blocks fall forward onto the next tread, and the new edge of the pavement is formed along the line of the succeeding gryke following the strike. The shapes of the pavements are thus intimately connected with the joint systems.

The second set of grykes are entirely solutional in origin, and have been produced in very recent times. The mode of formation can be appreciated by watching the movement of water on the clint surfaces during a heavy rainstorm. It runs across the surface in sheet flow, becoming concentrated into the furrows, and so is channelled into the deep grykes, where

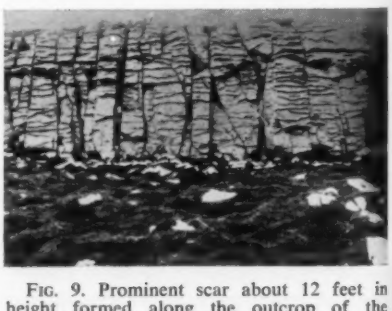

FIG. 9. Prominent scar about 12 feet in height formed along the outcrop of the 'Spotted Beds' of the *Lower Dibunophyllum* sub-zone in the Ingleborough district. Vertical jointing which runs parallel to the dip is exposed on the scar face.

solution will continue until the water is saturated. The mean hardness of this surface water, according to Corbel,[11] is 7, whereas the hardness of the slowly moving water at the base of the large grykes is probably as much as 8 or 9 as a result of the abundance of carbon dioxide derived from the decaying vegetation.

The Evolution of the Pavements

Having discussed the morphology and structure of the pavements, the next problem is that of discovering the processes which have led to their formation. The creation and maintenance of a bedrock surface, developed on a bedding plane, requires some process or set of processes, which, first, will remove or dissolve the debris accumulated from the dissection of the overlying bed, while the shale band or more resistant lamina is protecting the underlying bed (Figure 4), and which, secondly, will dispose of the debris that accumulates on the newly created pavement from the backwasting of the scar above it, and from the waste of its own decay. Three processes are available which might meet these two requirements, first, solution under present climatic conditions, secondly, glacial scouring, and thirdly, periglacial processes.

Under the present climatic regime precipitation is fairly heavy, amounting to 60 inches or more in the higher areas, and in some districts reaching 100 inches, while there are, on average, 230 days with rain each year. Snow remains for more than 50 days on the sheltered, shady slopes, and there are 100 days when frost is recorded. Corbel has estimated that the rate of corrosion under these conditions is equivalent to the lowering of the limestone surface by 0.070 mm. per year.[10] This is not very rapid, and examination of the pavements in the field suggests that it is not sufficient to cause active pavementation. The most striking feature of the pavement surfaces is the way in which debris is accumulating (Figure 10). In other words the pavements show signs of having been more perfect in the past. Present conditions are leading to their burial because solution is not sufficiently intensive to prevent the accumulation of debris derived from frost shattering and other processes. The grykes are being filled with residual material and colonized by vegetation (Figure 6), and the scars show varying degrees of degradation, from tumbled limestone blocks to scree slopes of constant angle (Figure 11). The scars and the pavements are thus being buried in the waste of their own decay and the process or processes which formerly kept them clear are no longer at work.

Fig. 10. Limestone pavement littered with debris and being colonised by vegetation on Hampsfell. The notebook indicates the scale.

Fig. 11. Pavements and scars in profile in the Morecambe Bay area, showing the almost complete vegetation cover on the pavements, and the debris accumulating beneath the scars.

The second possibility is that limestone pavements are relic features of the last glacial period; the movement of the ice across the surface forming ice scoured pavements, with a certain degree of structural control. There are two objections to this theory: first, the evidence, in the main, suggests that the higher areas remained ice free during the last glacial episode, that of the Late Dales glaciation in the Pennines, and the Scottish Readvance on the west coast. Yet it is the pavements at higher altitudes which are best developed at the present day, and it is unlikely that they could have remained as relic forms

since the preceding glacial episode, the Main Dales, and the Main Irish Sea glaciation. Secondly, if corrosion has been operative at no more than the present rate during the time since the last glacial episode, the mean lowering of the limestone surface would be approximately 36 inches,[11] enough to have entirely removed most small scale relic features.

The third possibility is that of periglacial weathering, and two distinct processes of this type may be considered. First, altiplanation aided by solifluction has been advocated as the process producing altiplanation terraces.[12] Material is separated from the parent rock by frost action, brought to the surface by heaving, and is then moved down slope by solifluction. In this way terraces in the bedrock may be formed, and some limestone pavements may have been affected by these processes. However in many cases this cannot have been the formative process because the pavements have a definite reverse slope into the hillside, so that the gravitational removal of material down the hillside could not have taken place, yet these pavements do not show the abundance of gelivation material which would be expected if altiplanation had been operative.

The second periglacial process is that of snowbank solution. Melt water from snow is very much richer in carbon dioxide than rain water. Studies in Finland have shown that the solubility of carbon dioxide is twenty times greater in snow than in water,[13] with the result that water at 32°F can hold three to four times the amount of limestone in solution as water at 60°F and so is a much more effective corrosive agent. The processes operating under snow banks, and in the pools of icy water produced by snow melt, would amount to an acceleration of the solution effects experienced at the present time, so that debris would be destroyed more rapidly, and would not accumulate on the pavement surface or beneath the scars. The shale bands would have an immunity to corrosion, as they do at the present, while the more resistant limestone bands would also exert some protective influence, and so the theory, discussed above, of the lithological control of pavement formation is not vitiated. Work by Manley[14] has shown that the climatic conditions in western Britain during the last phases of the glacial period would have been particularly favourable to intensive corrosion. During the Scottish Readvance glacial, the mean sea level temperatures are given as 45°F (July) and 16°F (January), compared with 60°F (July) and 41°F (January) at the present, while the precipitation in water equivalent greatly exceeded that of the present, and may have been 80 inches in the higher areas, reaching over 120 inches in some districts. With the Alleröd phase, temperatures were probably ameliorated to 52°F (July), and 17°F (January), and the succeeding Pre-Boreal period saw their decrease to 47°F (July), and 17°F (January). Throughout late-glacial and immediately post-glacial times the British Isles had a maritime climate, which would favour heavy snow fall especially on the western slopes, and provide abundant melt water with a high carbon dioxide content. Corrosion would be intensive while the shattering effects of frost activity characteristic of dry arctic climates would be comparatively ineffective because of the protecting snow cover, while gelivation debris that was produced would be dissolved very rapidly. Snow bank solution would seem to be the most likely process to remove the shattered debris already lying on the pavements. Such a solution would strip the bedding planes, and preserve both the sharp break of slope at the back of the pavement and the smooth pavement surface. It would also account for the uniformity of depth and size of the large grykes, which are similar to those being formed at the present time in the Alpine areas under comparable conditions of abundant melt water. The only other process which could account for all the observed features is long continued solution beneath cold water lakes or seas. Such solution has produced perfect pavementation in the Baltic Sea area, but in the absence of other evidence of high level water bodies in the northwest of England, such an explanation is untenable.

Conclusion

In conclusion a brief review of the evolution of the limestone pavements in the northwest of England may be presented. They were formed in late-glacial times as the result of snow bank solution, which

probably continued until as late as the Pre-Boreal of Pollen Zone IV, about 7,500 B.C. The large grykes developed along the joint systems also date from this period. With the rapid amelioration and reduced precipitation of the Boreal and Atlantic periods leading to the "climatic optimum," solutional activity and gelivation were reduced in intensity and the colonization of grasses continued fairly steadily. The vegetation cover may have been more extensive during the "climatic optimum" than at present, and in some areas the pavements show signs of having carried a vegetation cover at some period prior to the present. The pavemented surfaces that remain in the present landscape owe their preservation in part to the warmer and dryer conditions with less solutional activity and considerably less gelivation, which existed from about 5,000 B.C. to the Roman period. At the present the pavements are in a process of fairly rapid decay with the accumulation of debris on the surface, and the formation of shallow grykes.

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RÉSUMÉ

On peut observer dans le pays de craie datant du Carbonifère Inférieur et situé dans le partie nord-ouest de l'Angleterre quelques-uns des meilleurs exemples de topographie karstique que l'on puisse trouver dans les Iles Britanniques. Le paysage est marqué de pavés calcaires qui abondent dans tout le territoire.

L'auteur discute de la formation de ces pavés en rapport avec la nature et la disposition des lits rocheux et démontre qu'il y a eu une influence bien définie de la structure. Il existe une relation entre les pavés les plus étendus et les dépôts calcaires les plus massifs, bien que, dans certains cas, la présence d'une bande schisteuse superficielle puisse avoir été un facteur plus important dans la formation des pavés que le degré de résistance du calcaire lui-même. La disposition des sillons de dissolution les mieux marqués (grykes) est généralement symètrique et correspond au système de fissuration et à l'inclination des couches. Certaines grykes en voie de formation et d'autres phénomènes de dissolution moins marqué, dont la distribution n'est pas régulière et qui semblent résulter, dans les conditions climatiques actuelles, d'une décomposition souterraine, conduisent rapidement à la dissection et à la réduction des pavés.

On peut donc se demander quels facteurs ont été en jeu dans le développement initial des pavés. L'auteur étudie quatre hypothèses: dissolution dans des conditions climatiques semblables à celles qui existent présentement; burinage glaciaire; cryoplanation, et nivation.

En conclusion, l'auteur retrace l'évolution des pavés calcaires de cette région en rapport avec les conditions changeantes du climat et de la végétation au terme de la période glaciaire et au cours de la période post-glaciaire. Il suggère que cette évolution a été semblable à celle qui a eu lieu dans d'autres régions ayant été témoins d'une histoire paléoclimatique comparable.

A NOTE ON THE POLITICAL GEOGRAPHY OF THE INDIA-CHINA BORDER

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INDIA AND CHINA are the two most populous states in the world; together they contain more than a third of the world's population. Each of these Asian giants is currently experiencing a revolution, different in method, in degree, and in impact, but geared to the common purpose of achieving prosperity, power, and prestige. Each is politically resurgent, each is capable of leadership in Asia, and each professes internal and international peace. At the Afro-Asian Conference not too long ago, both jointly pioneered a programme of peace known as the Compact of "Panch Shila." This was partly to allay the fears of the smaller Asian countries, and partly to demonstrate to the world the need for universal amity. The programme had hardly begun when India and China suddenly found themselves embroiled in a bitter dispute and, indeed, armed conflict over the control of rather useless territory along their mutual border. The situation thus precipitated has caused considerable frustration and embarrassment to both nations, and has also aroused much comment and concern abroad.

An appraisal of the published examinations of the dispute reveals two weaknesses. First, such analyses are confined to the specific areas in dispute in the northeast and the northwest of the Indian Republic without due recognition of the nature of the zone of which these areas are but small parts. Secondly, despite the fact that a national boundary is so obviously a geographical as well as a political feature, emphasis has so far been placed primarily on the political aspects. Because of this, the assessments of the situation to date are incomplete, unsatisfactory, and often confusing.

Time and space do not permit a detailed investigation of this problem. This note, therefore, attempts to demonstrate how even a brief appreciation of the physical, cultural, economic, and political traits of the geography of the zone containing the disputed areas helps to elucidate the problem. In addition, reference is made to the basic economic and political rivalry between modern India and China and the part this has played in detonating the dispute.

Physically, the India-China boundary occupies various sections of the highly mountainous rim extending from the Arabian Sea to Burma across the north of the Indian peninsula. This rim is corrugated by ranges of different lengths, widths, and altitudes lying closely en echelon. They are also broken by many difficult but tempting saddles and passes and by a number of large and small antecedent river valleys. Many of these breaks have functioned as corridors of settlement and transit from the earliest known times; e.g., the passes and the valleys of the well-known Northwest Frontier, the valley of Ladakh, and the middle sections of the Brahmaputra—all in varying degree, ideal havens of refuge and traditional highways of invasion or migration. The unsurveyed, ill-marked, ill-defined India-China boundary occupies some of the most complex sections of this mountainous zone (Figure 1).

Corresponding complexity is also apparent in the ethnic and cultural configuration of the zone. The intrepid, unpredictable Pathans of the Western Frontier where Kipling found his heroes and villains are succeeded northwards by the isolated and suspicious Kaffirs of the Kohistan and Pamir slopes. Eastwards lie the jagged and wild altitudes of the Karakoram where the upper Indus has incised a deep, narrow valley. This valley is virtually cut off from the rest of India, but it is connected by extremely difficult passes to Tibet and Sinkiang. Recessed in its depths is a small Buddhist community composed initially of the descendants of refugees from the ag-

FIGURE 1.
PHYSICAL FEATURES
PAMIR
KOHISTAN
KARAKORAM
NORTH WEST FRONTIER
Indus
LOW LAND
HIMALAYAS
Brahmaputra
INDIAN PENINSULA
Ganges
Arabian Sea
Bay of Bengal
FIGURE 2.
CULTURAL GROUPS
KAFFIR
LADDAKHI
PATHAN
PUNJABI
LEH
TIBETAN
GURKHA
NEPALI
SIKKIMI
BHUTANI
ABORIGENES
Edge of Mountainous Land
INDIAN
SHAN
CHIN
FIGURE 3.
POLITICAL BOUNDARIES
AFGHANISTAN
KASHMIR
WEST PAKISTAN
TIBET
CHINA
NEPAL
SIKKIM
BHUTAN
INDIA
BURMA
SCALE
500 MILES
FIGURE 4.
U.S.S.R.
TIBET
AFGHAN.
DISPUTED AREAS
Lhasa
MC MAHON LINE
Brahmaputra
CHINA
DISPUTED
AREA
Indus
KASHMIR
LADDAKH
U.N. CEASE FIRE LINE
Srinagar
Leh
KHURNAK PASS
LANAK PASS
WEST PAKISTAN
INDIA
SHIPKI PASS
TIBET
EAST PAKISTAN
BURMA
100 MILES

gressive Brahminism of early India and the aggressive imperialism of medieval China. This community centres around Leh or Ladakh, the Buddhist capital and symbol of refuge, peace, and even prosperity.

Parallel to the Karakoram in the south and west lie the bold and bleak westernmost ranges of the Himalayas. Farther east, where the Ganges and its tributaries cut across the Himalayas, is the land of the warrior Gurkhas who are completely different in aptitude and profession from the Buddhist monks of Ladakh. The Gurkhas are professional mercenaries and have scant recognition for political boundaries. They are ever eager to enlist for service in the armed forces and mountaineering expeditions controlled by Nepal, India, and Tibet alike. Farther east again, the border between Tibet (China) and India is ethnically and culturally peripheral to both the Indian and the Chinese regimes. It is beaded with small groups with distinctive entities, for example, the inhabitants of Nepal, Bhutan, and Sikkim. All of these are simultaneously the dwellers of the 'terai,' the low, swampy ribbon produced by the streams descending the Himalayas, as well as of the steep slopes rising to some of the highest altitudes in the world. East of Bhutan, the terrain is too difficult to provide support to any but unknown, isolated aboriginal groups. Probably these groups are either the remnants of the old Sinitic tribes that crossed into Bengal in early days or are distant relatives of the Naga headhunters of Assam and the Shan and Chin tribes of northern Burma (Figure 2). To sum up, the India-China boundary traverses a highly varied cultural zone where sometimes the individual groups are politically defined and sometimes not.

The lack of integration between physical, cultural, and political aspects of the zone is, in part, responsible for the highly unstable and controversial political behaviour of the mountainous borderland. Such behaviour can be seen in the trilateral rivalry along the Durand Line of the Northwest Frontier where Pakistanis, Afghans, and Pathans became bitterly involved in the issue of Pakhtoonistan (a so-called independent Pathan state). Similarly, farther east the disposition of the princely state of Jammu and Kashmir with overwhelming Moslem majority but pronounced Hindu and Buddhist minorities is still in dispute and remains politically explosive. The Chinese incursions into and occupations of parts of Ladakh, which lies within the same state, further confound the situation there. The status of Nepal, Bhutan, and Sikkim has also acquired a new significance in the light of India's assumption of the right and the duty to 'protect' the territorial integrity of these states, and of China's assumption of a stricter control over Tibet. This matter was highlighted recently by the visit of China's Prime Minister to Nepal, and his offer of accurate delineation of the Tibet (China)-Nepal boundary. Nor should one forget that it was through Sikkim that the Dalai Lama escaped into India and frustrated his Chinese pursuers. To fortify their border in this part, the Chinese have laid claim to thousands of square miles of territory in the region of the McMahon Line which only theoretically defines the India-China boundary here. This action may also be designed to elicit a greater degree of co-operation from the small states in this area.

As the economic potential of the mountainous border zone is very poor, its economic geography is relatively simple compared to the complex physical, cultural, and political aspects outlined above. Altitude, climate, and terrain limit agriculture, and geology and difficult access inhibit the prospect of mineral development on any significant scale. Even the hydro-electric potential is limited because of the meagre volume and short duration of the water flow in the streams. Modern transportation routes are most expensive to construct and maintain. Thus the entire zone is likely to remain relatively undeveloped and isolated. Under these circumstances, the border issue created by China becomes rather incomprehensible. To understand it, one therefore has to enter fields that are not confined to the border zone but which actually span the wider horizons of the political geography of southeast Asia—the possible future theatre of Indian-Chinese rivalry.

Most authorities believe that it is not Europe or the Western world but the poverty-stricken emergent nations of Asia and Africa which are the future proving

grounds in the contest between the West European form of democracy and the East European experiment in communism. India has been desperately trying to cling to the former, China has been resolutely practising the latter. Apparently the rest of the Asian countries facing many problems similar to those in India and China are likely to adopt the ways of the winner. The record of the last ten years indicates that while the Chinese have been able to make considerable progress, the Indians have faced great difficulty in maintaining even past standards. This was illustrated clearly by the failure of India's first Five Year Plan, and again by India's obvious inability to finance the more ambitious second Five Year Plan on its own.

In the summer of 1959, the Indian Government was forced to seek substantial increments in American aid, and it sent an official delegation to the United States for this purpose. In Chinese minds, however, the grant of American aid is associated with rather sinister fears. It was possibly at this time that the Chinese first became suspicious of the integrity of India's declared neutralism and a tendency towards closer relations with the United States. On the heels of this suspicion came the political crises in the Indian state of Kerala. The democratically elected Communist government of Kerala was summarily, and, in the Chinese view, rather undemocratically dismissed from office. This, of course, was a serious blow to the prestige of Communism as a whole and gave added strength to Chinese suspicions of a growing pro-Western and anti-communist tendency of the Indian government. It was during this deteriorating climate of India-China relations that the Chinese carried out their long-prepared plan to reduce the power of the Dalai Lama in Tibet, and to bring Tibet into line with other outlying areas within their sphere. This policy resulted in the dramatic flight of the Dalai Lama to India. Instead of returning him as 'a criminal in flight' who, according to the Chinese, must be repatriated, the Indian government received him with traditional effusive Indian hospitality. At the same time, India, along with many other nations, expressed criticism, disappointment, and alarm at the Chinese policy in Tibet. This was bitterly resented by the Chinese, and put a seal on their mounting suspicions of India.

The Chinese apparently decided the time was now ripe to express their resentment in a more definite way. In the latter part of August, 1959, reports of Chinese incursions on the northeastern and northwestern border areas of India began to circulate. These were followed by actual armed clashes in Ladakh as well as in Assam, resulting in the death and capture of a number of Indian soldiers, and in the Chinese occupation of territory claimed by India as its own. These areas are at an altitude exceeding 15,000 feet. Accessible from Tibet by newly built roads, they have hardly any connections with India, and thus the strategic advantage in these places lies with China. Since the Indians were unable to supply adequate protection to these areas, and as they were anxious not to aggravate the situation, the Chinese have retained control over the territory they have occupied (Figure 4). According to them this is but a fraction of the territory which should be theirs.

Since both sides have shown great intransigence towards a compromise, the stalemate remains. To China the cost is a decrease in the goodwill and an increase in the fears of other Asian nations, which they hope time will heal. To India, the dispute is more costly because it necessitates diversions of large slices of national capital for military expenditures required to maintain a state of preparedness in the event of a possible spread of the border conflict. With funds so greatly reduced, India's second Five Year Plan seems to be in even greater jeopardy than was the first Plan. During all this time, however, China continues to progress in its programme of economic development. Accordingly the gap between the economic achievements of India and China grows wider, the balance remaining, of course, in China's favour. The latter clearly hopes that these achievements will be impressive enough for other Asian nations to emulate.

It is thus only by looking at the situation in situ as well as in its wider context that the India-China border dispute ceases to be an enigma. It is explicable in a rational and perhaps even satisfying way, but only by integrating the facts of politics and history

with those of geography. This brief note is designed merely as an illustration of how such an integration is possible. It ends in the hope that other geographers would undertake more comprehensive investigations along these and similar lines.

RÉSUMÉ

L'Inde et la Chine traversent une période de révolution. Bien qu'on puisse reconnaître des différences de méthode, de degré et d'intensité, il existe dans les deux cas des objectifs communs: prospérité, puissance, prestige. Malgré le pacte de paix, connu sous le titre de "Panch Shila", qui lie les deux pays, ces derniers en sont venus récemment à une brouillerie acrimonieuse et même à un conflit armé au sujet de certaines portions de territoire limitrophes, qui sont sans réelle valeur.

Les commentaires publiés jusqu'à date ont, en général, porté exclusivement sur ces parties de territoire en dispute et n'ont pas tenu compte de facteurs assez complexes se rattachant à la géographie d'une zone beaucoup plus vaste, dont les pièces en question ne représentent que des parcelles assez minimes.

Le but de cette note est de démontrer comment l'examen des traits physiques, humains, économiques et politiques de cette zone peut aider à mieux comprendre le problème.

Le comportement des groupes habitant cette région montagneuse est caractérisé par l'instabilité et la controverse. Ce comportement a été rendu plus erratique encore par les incursions chinoises et l'occupation par la Chine de certaines parties du territoire limitrophe. Ces incursions, dans une région relativement vierge et isolée, et dont la condition ne changera vraisemblablement pas, ne s'expliquent ni par des considérations économiques, ni par la géographie du territoire.

L'auteur est d'avis que ces invasions sont dues en partie au fait que la Chine doute de plus en plus de la neutralité de l'Inde et en partie aux avantages stratégiques, tant au point de vue politique que militaire, que la Chine prétend en retirer. De plus, la Chine conserve un vif ressentiment à l'endroit de l'Inde, à la suite du refus de celle-ci de repatrier le Dalaï-Lama et de ses critiques de la politique chinoise au Tibet.

La querelle persiste et l'auteur indique qu'elle est plus coûteuse à l'Inde qu'à la Chine. Avec l'affermissement graduel de la supériorité de cette dernière dans le domaine économique, son influence auprès des autres nations d'Asie deviendra de plus en plus considérable.

La mise en rapport des faits politiques, historiques et géographiques peut, dans certains cas, fournir une explication rationnelle et adéquate des problèmes de politique nationale et internationale tels que ceux qui ont trait présentement à la frontière sino-indienne.

WAVE TRANSPORT OF BEACH MATERIALS ON LONG POINT, LAKE ERIE

HAROLD A. WOOD
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IT IS GENERALLY ACCEPTED by geomorphologists that in the development of shorelines the most important modifications are effected by waves. The winds which generate them are only directly operative above water level, and in most cases the currents which are significant geomorphologically are those generated by the waves themselves. Nevertheless, exact information concerning the effect of waves upon a coast has been slow in coming, for quantitative studies of shore morphology are extremely difficult to carry out. The direct measurement of waves is too costly a procedure for most research programmes, and wave tank experiments are of limited value as they cannot duplicate the great storm waves which are the most significant agents of shore modification.

It is the purpose of this paper to demonstrate the application of an alternative quantitative approach to the problem of shifting shorelines based solely on data readily available in wind records and on hydrographic charts. Admittedly the accuracy of the method is only approximate. Now and then, as in many investigations, progress has had to wait upon the making of assumptions which may not be entirely true. Nevertheless, the approach does permit the study of shoreline processes without elaborate equipment, and even in the single application here presented, it points to several important conclusions.

The area selected for study is Long Point, a sand spit on the north shore of Lake Erie. Long Point is probably the most spectacular feature of shore deposition in the Great Lakes and offers ideal conditions for an investigation of this type. Not only is Lake Erie free from the tides which complicate studies of marine coasts, but its surrounding weather stations provide more complete wind records than would normally be available for an oceanic site. Furthermore, surveys made in 1853, 1907 and 1951 show Long Point to have been subject to extremely rapid growth. In the approximately 4000 years of its existence, the spit has attained the remarkable length of twenty-five miles. This rate of growth is a result, in part, of the coincidence of the prevailing southwest winds and the maximum length of fetch on Lake Erie, and in part of the abundance of beach-building materials available in sand cliffs to the west. Even though the spit is now being extended into water about 150 feet deep, it has been increasing in length over the past century by an average annual amount of 20 to 25 feet.

Long Point has not only been growing; it has been changing in other ways as well. The major alteration to have occurred was a breaching of the neck of the spit early in the Nineteenth Century. Maps published in 1798 and 1817 show the point to be continuous, and early travellers tell of portaging across the isthmus. However, by 1839 a channel a mile wide and fourteen feet deep had been formed across the western end of the Point. This channel was regularly used for navigation, and its position was marked by a light ship. Fourteen years later, in 1853, it was still five-eighths of a mile wide.

It is not known exactly when the gap was completely filled, but by the beginning of the present century the spit was once again joined to the mainland. A shallow bay, however, still marks the position of the former breakthrough, and in this bay deposition is still occurring. In Long Point there is, therefore, a departure from the classical situation in which a spit is divided simply into two sections, a prograding tip and a retrograding neck. Clearly Long Point contains at least two prograding and two retrograding sections, a fact which adds considerably to its value as a subject of investigation. The fact of the breakthrough also adds a note of immediate practical significance to the study, for the area is undergoing rapid recreational development. If Long Point is once again to be broken in two by the waves, it is highly

desirable to know approximately where the breach is likely to occur, and when.

The starting point in this inquiry is to ascertain the magnitude of the prime force producing shoreline changes: the energy of the waves. Theoretically this should pose few difficulties as the energy of a deep water wave is known to be proportional to the product of its period and height, both squared,[1] while a graph has been constructed permitting the determination of these wave characteristics when wind velocity and duration and the length of fetch are known.[2] Unfortunately, however, wind records are not normally compiled in such a fashion as to reveal directly the velocity and duration of individual gales or breezes. In the records winds are divided into different velocity groups, but durations are only indicated in terms of total hours per month or year. A further problem is that the weather stations around Lake Erie[3] differ considerably in the winds which they experience, and no single station's records can be taken to the exclusion of the others as the waves which affect Long Point come from all parts of central and eastern Lake Erie, and are developed under the influence of the winds of this wide area (Figure 1).

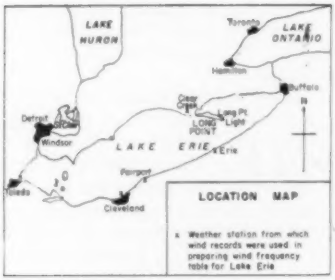

FIG. 1

The latter difficulty was met by accepting, as far as possible, the highest velocities (for winds of each direction) recorded at any of the stations, a procedure aimed at minimizing the influence of local reduction of wind velocities due to friction over the land. Average wind velocities for the different velocity groups were then easily determined using the records of wind mileage available for most stations. The results are summarized in Table 1.

TABLE 1
WIND FREQUENCIES, LAKE ERIE
(Showing per cent of total time during which wind of each class blows)

Wind direction	Wind velocity		
	0–12 m.p.h. (Average 7.45 m.p.h.)	12–24 m.p.h. (Average 16 m.p.h.)	Over 24 m.p.h. (Average 27.7 m.p.h)
North	4.5	1.9	0.48
Northeast	9.03	4.45	1.2
East	4.66	1.8	0.18
Southeast	5.57	0.80	0.10
South	8.40	1.96	0.40
Southwest	13.63	7.7	2.4
West	8.15	5.73	1.9
Northwest	7.31	4.47	1.60

The duration of individual gales is more difficult to estimate without running through the day to day wind records, a process which would usually be prohibitively time-consuming. In the present instance, a short cut was taken by assuming that winds of over 12 m.p.h. will occur during the passage of low pressure systems while those of under 12 m.p.h. will be associated with highs. From a recent analysis of the occurrence and frequency of cyclones in the northern hemisphere[4] it may be calculated that the average time required for the passage of a cyclone over Lake Erie is about 60 hours, while the corresponding figure for an anticyclone is 200 hours. When these amounts of time are divided among winds of various directions in accordance with the frequencies shown in Table 1, it is possible to obtain

TABLE 2
WIND DURATIONS, LAKE ERIE
(in hours)

Wind direction	Wind velocity		
	0–12 m.p.h.	12–24 m.p.h.	Over 24 m.p.h.
North	14.0	5.9	3.5
Northeast	28.0	13.8	8.7
East	14.5	5.6	1.31
Southeast	17.3	2.48	0.73
South	26.1	6.1	2.9
Southwest	42.3	23.9	17.4
West	25.3	17.8	13.8
Northwest	22.7	13.9	11.6

values for the average durations of individual gales and breezes by wind strength and direction. These are shown in Table 2.

The way was now clear for the evaluation of wave heights and periods, using Bretschneider's graph, and hence of the energy of the waves corresponding to wind groups of Table 2. These figures, multiplied by the frequency values of Table 1, were plotted for the eight points of the compass and for various lengths of fetch. The graphs were completed by the drawing of smooth curves, with the results shown in Figures 2, 3, and 4. Upper limits to the energy values were set in general by wind durations, but in a few cases by the length of fetch on Lake Erie. Using these graphs it was possible to obtain an index of the wave energy for winds of each velocity group for any wind direction and any length of fetch.

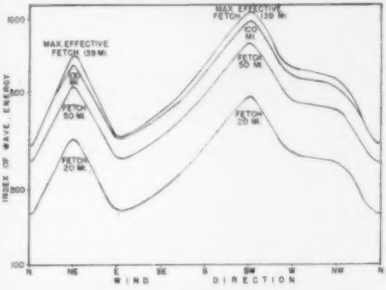

FIG. 2. Wave energy generated by winds of under 12 m.p.h. on Lake Erie.

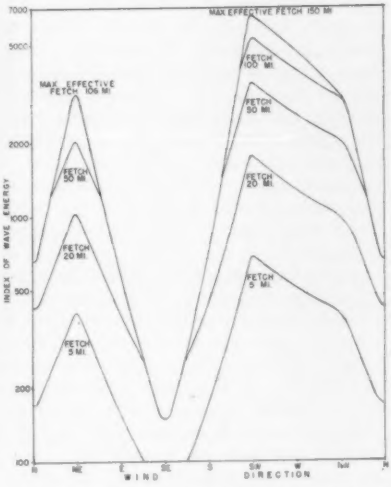

FIG. 3. Wave energy generated by winds of 12–24 m.p.h. on Lake Erie.

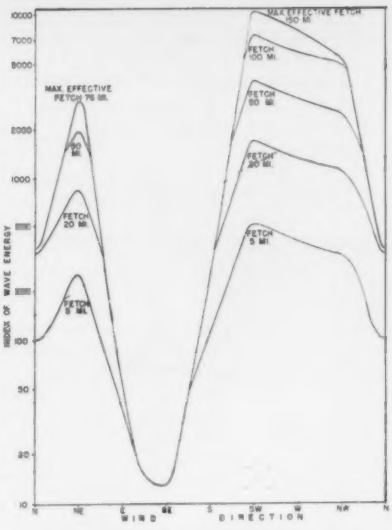

FIG. 4. Wave energy generated by winds of over 24 m.p.h. on Lake Erie.

This energy, however, is not uniformly distributed along the shore. Because of wave refraction, there will be a concentration of wave energy in certain sections, and a diffusion in others. The effect may be evaluated by the drawing on a chart of orthogonals, or lines perpendicular to the wave crests, from deep water to the shore using standard techniques of refraction diagram construction.[5] The interval between orthogonals in deep water divided by the interval at the shore provides a refraction coefficient which can be multiplied by the wave energy in deep water to give the amount of energy per unit of shore length. Values of this coefficient were worked out for winds coming from each 10° of the compass,[6] and selected results are shown graphically in Figure 5. The reference points may be located on the map of Long Point, Figure 6.

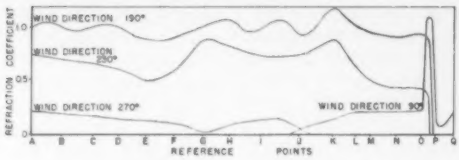
REFRACTION COEFFICIENT
WIND DIRECTION 190°
WIND DIRECTION 250°
WIND DIRECTION 270°
WIND DIRECTION 310°
A B C D E F G H I J K L M N O P Q
REFERENCE POINTS

Fig. 5. Refraction coefficients for selected wind directions.

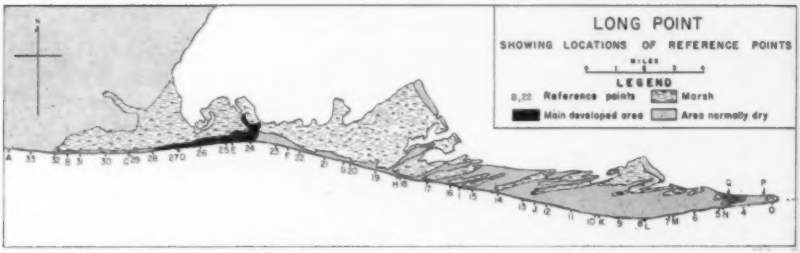

FIG. 6

Concerning the disposal of this energy, the first distinction to be made is between that part of the energy which is exerted perpendicular to, and that part which is exerted parallel to the shore. The effect of the former is to move materials directly both landward and seaward. In general, large waves remove materials from the shore, while small ones restore it,[7] but clearly, the two movements would not normally cancel each other out, as in most areas there must be a net loss of substance from the land. Unfortunately, it is not easy to determine directly how much energy is used to bring in sand, and how much to carry it away, yet it would not appear that on Long Point there are large local variations in the energy expended in this way. Consequently, the geomorphic significance of energy expended at right angles to the shore will be assessed indirectly below.

With energy expended parallel to the shore, the situation is different. In this case, the net direction in which the energy is applied remains essentially constant. The effect of this is to move materials in one direction, which, for clarity, will be referred to as "downshore," and as the quantity of material transported increases or decreases downshore, erosion or deposition will occur. The influence of this energy upon shore development will therefore be the more readily evaluated.

The fraction of the total energy which is applied parallel to the shore is, of course, represented by the sine of the angle between wave and shore. However, since this angle becomes continually smaller as any wave approaches the shore obliquely, it becomes necessary to decide where it should be measured. Since most of the wave energy is released after it breaks, it seemed reasonable, in the present study, to measure the angle at the breaking point and again at the shore and to average the two sines together.[8] The results, in a graphical form which permits the ready evaluation of this factor for any wave which might occur on Lake Erie, appears in Figure 7

Using the procedures outlined above, a calculation was made of the energy expended parallel to the shore at each of seventeen reference points, for winds from each 10° of azimuth and of each of the velocity groups. For each reference point the sum of the energies directed westwards was subtracted from the sum of those pushing eastwards, the former being always the greater except in the case of the two reference points on the north side of Long Point. For convenience each figure was

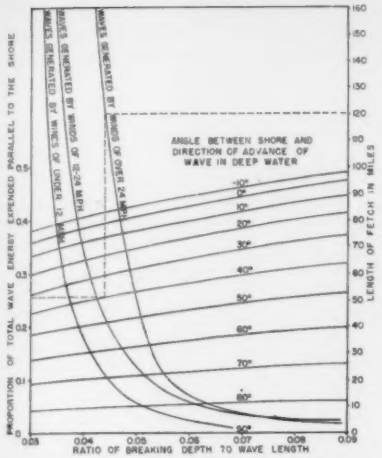

FIG. 7. Proportion of total wave energy expended parallel to the shore on Lake Erie; e.g., for length of fetch 120 miles and winds of over 24 m.p.h., with deep water waves advancing at an angle of 40° with the shore, the proportion is 0.256.

TABLE 3

WAVE ENERGY EXPENDED PARALLEL TO THE SHORE

Reference point	Easterly component	Westerly component	Net flow of energy		Energy flow as % of value at B (Transportation index)
A	11719	548	11171	Easterly	94.8
B	12349	585	11764	"	100.0
C	11890	553	11347	"	96.4
D	11064	459	10605	"	90.2
E	9063	328	8735	"	74.3
F	6229	642	5587	"	47.5
G	8893	764	8129	"	69.1
H	10949	683	10266	"	87.2
I	10205	620	9585	"	81.5
J	9267	627	8640	"	73.5
K	10628	710	9918	"	84.4
L	10167	789	9369	"	79.7
M	8736	655	8081	"	68.7
N	5834	629	5205	"	44.3
O	5859	874	4985	"	42.4
P	1284	1800	516	Westerly	4.4
Q	1083	2419	1336	"	11.4

then expressed as a percentage of the value at B, the point where the spit connects with the mainland, with results as summarized in Table 3. If it is assumed that there will be no significant local variation in the proportion of energy used in the transport of material, the last column of Table 3 becomes in actuality an index of downshore transportation.

This index, in turn, may be expressed in terms of the actual volume of materials moved, a most fortunate circumstance which derives from the very rapid growth of the spit, and the depth of water into which it is being built. Long Point is advancing so rapidly that, as indicated above, its annual increase in length is at least twenty feet. As it is also being extended at a large angle with the bottom contours, it is a simple matter to fix the original position of these contours by linking them across the tip of the spit. This permits the drawing of sections across the spit showing the original as well as the present lake bottom. In this way the cross section of the spit at its tip was found to have an area of 228,000 sq. yds., from which it follows that the annual average addition of material to the tip of the spit is approximately 1,500,000 cu. yds. This figure, however, corresponds to a net transport index of 38.0, a value representing the difference between additions to the tip on the south and removals on the north. Consequently, each index point is equivalent to the transport of approximately 40,000 cu. yds. of beach materials per annum.

Before attempting to relate the volume of materials transported along the shore and the actual rate of shoreline advance or retreat, three other factors should be considered: the offshore gradient, the amount of material in the offshore section of the spit, and the size of particles being transported.

The offshore gradient would appear to have a bearing on whether erosion or deposition will be concentrated at the beach or out in the lake, though on Long Point the significance of this factor must be quite limited, for it is related primarily to the past. Where the shoreline has retreated, the water offshore is shallow. Where it is advancing, the water is deep. Nevertheless, the average gradient has been measured as far as the 7-fathom contour, the depth

which agrees most closely with the limit of offshore wave deposition as shown by the contours themselves, as well as by theoretical considerations.

The amount of material extant in the offshore parts of the spit deserves consideration, for this represents the present status of Long Point as much as does its actual shoreline. In a dynamic study, the change in this volume as one proceeds downshore will be the most significant element, and this has been determined from hydrographic data with the results summarized below.

Finally, the size of particles being transported might be significant inasmuch as larger ones would be moved only by larger waves. No sampling was made, but in view of the fact that all materials in the spit originated in the sand bluffs to the west, it was assumed that variations in particle size downshore would be small, and due primarily to abrasion in transit. The distance from the neck of the spit can therefore be expected to give a reasonable inverse index of the size of particles.

The results of all these calculations for thirty stations on the south shore of Long Point are given in Table 4 below.[9]

The relationship between the five elements of Table 4 has been worked out statistically, with the following results:[10]

Equation: $A = -10.13 + .0225\ B + 16.32\ C + .00895\ D - .327\ E$

Multiple correlation coefficient: $r_{A\cdot BCDE} = 0.727$

Simple correlation coefficients: $r_{AB} = 0.656$; $r_{AC} = 0.186$; $r_{AD} = 0.352$; $r_{AE} = -0.033$

The standard error of estimate: $s_c = 7.73$

It will be noted that the correlation is by no means perfect. There are many reasons for this. One is the limitation of the number of factors considered; another, the inaccuracies of the assumptions made in evaluating them. The hydrographic charts may not be entirely accurate, and, in addition, the average yearly change in position of the shore from 1907 to 1951 is not in every case equal to the present rate of change. It must further be borne in mind that the ideal equation may incorporate the elements of Table 4 in powers other than the first, but time has not permitted the examination of this possibility.

TABLE 4

SHORELINE CHANGE AT LONG POINT

NOTATION: A = Average annual shift in position of shore 1907–1951 in feet. (positive = aggrading shore; negative = retrograding shore)
B = Net additions of material produced by downshore movement, in 1000 cu. yds. per mile of shore per annum.
C = Offshore slope in percent.
D = Downshore change in volume of offshore portion of spit, per mile of shore, in 1000 cu. yds.
E = Distance from neck of spit in miles, downshore.

Point No.	A	B	C	D	E
4	− 4.5	19.75	1.26	−380	24.34
5	− 5.7	158	.969	−425	23.49
6	2.3	592.5	.795	−230	22.66
7	− 2.3	473	.764	− 65	21.77
8	3.9	296	.736	−150	20.94
9	2.3	79	.685	−145	20.08
10	4.5	−138.2	.652	−230	19.26
11	− 6.8	−276.1	.576	−380	18.38
12	−11.4	−150	.513	−350	17.51
13	− 6.1	59.3	.467	−395	16.66
14	− 6.8	197.5	.418	−330	15.80
15	0	256.5	.391	−355	14.94
16	−18.2	185.5	.361	−245	14.05
17	−31.8	86.8	.350	−190	13.23
18	−18.2	−197.5	.337	−140	12.33
19	−15.9	−414.5	.328	−160	11.51
20	−22.7	−477	.314	−600	10.64
21	−28.4	−481	.282	−150	9.76
22	−26.6	−355	.279	−150	8.88
23	− 3.4	197.5	.268	−205	8.03
24	3.4	592.5	.263	− 5	7.15
25	9.1	426	.267	130	6.33
26	6.8	296	.274	225	5.46
27	2.3	189.5	.286	320	4.61
28	6.8	138.1	.302	305	3.75
29	8.4	118.5	.317	155	2.90
30	0	98.6	.320	40	2.06
31	−7.3	19.75	.324	190	1.20
32	−9.3	−59.3	.342	385	0.35
33	−6.8	−130.3	.375	500	−0.48

Although the correlation is only approximate, it is still significant, and several points are worthy of note. First, both the offshore slope and the distance from the neck of the spit have a low degree of correlation with the shift in position of the shore. As indicated above, this is not entirely unexpected. The most significant variable in explaining shore aggradation or retrogradation is the addition or removal

of materials by downshore movement, while of intermediary importance is the variation in the volume of the offshore slope.

If C and E in the equation of Table 5 are assigned their average values and treated as constants, the following approximation is reached:

$$A = -6.45 + 0.0225\ B + 0.00895\ D.$$

This expression lends itself to graphical representation, and is shown thus in Figure 8. It points, furthermore, to a number of important relationships which are here advanced as tentative conclusions:

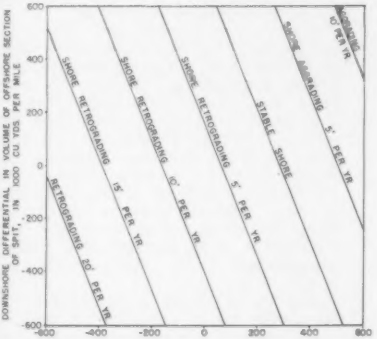
DOWNSHORE DIFFERENTIAL IN VOLUME OF OFFSHORE SECTION OF SPIT, IN 1000 CU YDS PER MILE
SHORE RETROGRADING 15' PER YR
SHORE RETROGRADING 10' PER YR
SHORE RETROGRADING 5' PER YR
STABLE SHORE
SHORE AGGRADING 5' PER YR
AGGRADING 10' PER YR
RETROGRADING 10' PER YR

FIG. 8. Amount of material annually added or removed by downshore transportation, in 1000 cu. yds. per mile.

1. The shore of Long Point may be retrograding even though considerably more material is being brought in by lateral wave transport than is removed in the same fashion.

2. Where the volume of the offshore section of the spit is uniform, approximately 290,000 cu. yds. of beach materials per mile must be brought in by lateral movement each year to maintain a stable shore. Each change of five feet per year in aggradation or retrogradation of the shore is equivalent to a further addition or removal of 220,000 cu. yds. of materials annually per mile.

3. Retrogression of the shore tends to be considerably greater where the volume of the offshore part of the spit decreases downshore, and less where it is increasing. However, only when the annual increase is greater than 700,000 cu. yds. per mile will the shore tend to aggrade even though materials are being removed from it by wave transportation downshore.

Finally, since the discrepancies between the change in volume of the offshore part of the spit and the amount of materials added or removed by wave transport downshore must be accounted for by transportation at right angles to the shore, the data shown in Figure 8 give at last a means of evaluating this elusive quantity. It is shown graphically in Figure 9, on which the following additional conclusions are based:

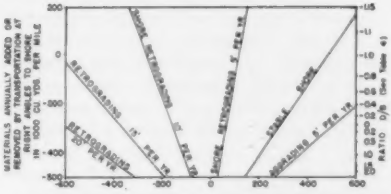
MATERIALS ANNUALLY ADDED OR REMOVED BY TRANSPORTATION AT RIGHT ANGLES TO SHORE, IN 1000 CU YDS PER MILE
SHORE RETROGRADING 15' PER YR
SHORE RETROGRADING 10' PER YR
SHORE RETROGRADING 5' PER YR
STABLE SHORE
SHORE AGGRADING 5' PER YR
RETROGRADING 10' PER YR
RETROGRADING 15' PER YR
RATIO D/B (See Table 6)

FIG. 9. Amount of material annually added or removed by downshore transportation, in 1000 cu. yds. per mile.

4. The amount of material moved at right angles to the shore is a function of the ratio D/B, where D is the downshore change in volume of the offshore part of the spit, and B is the amount of material added or removed by lateral wave transport. Only where the ratio is less than —1.0 is there a net addition of materials to the shore by movement at right angles to it. In most sections there is a large annual net loss of material by direct seaward movement.

5. The net amount of material moved at right angles to the shore is comparable to that moved parallel to the shore.

6. Additions of material to the shore by direct landward movement occur mainly where the shore is retrogressing at a slow or moderate rate. Rapid removals of material from the shore may occur on aggrading shores as well as on rapidly retrograding ones.

CONCLUSION

Wave energy, the most significant factor in effecting shoreline change, can be evaluated from point to point along a shore using information obtained from wind

records and hydrographic charts. Under favourable circumstances, it is also possible to ascertain the amount of material being transported in a given period of time by a given amount of energy expended parallel to the shore.

On Long Point the rate of shoreline change is correlated with the amount of material being added or removed by lateral wave transport, as well as with the downshore variation in volume of the offshore part of the spit. However, most parts of the shore are retrogressing due to large annual removals of material seaward.

Although it is beyond the scope of this paper to do so, the relationships discovered will permit a prediction of future changes on the shore of Long Point. For example, even a cursory examination indicates that the next breakthrough by waves across the spit will occur in the vicinity of reference point I and in about 200 years. It would appear likely, moreover, that the results of the study might well be applicable to other sand spits as well, provided the materials of which they are composed are similar to those of Long Point.

Finally, in pursuing a study of this type, one is struck by the limitless possibilities for further refinement in the method employed. This should not be taken, therefore, as the final word on the subject, but simply as the result of one stage in the search for a more complete understanding of beach morphology.

REFERENCES

1. From $E = LH^2$ (Johnson, D. W.: *Shore Processes and Shoreline Development*, New York, 1919.) and

$$L = \frac{g}{2\pi} T^2$$

(Krummel, O.: *Handbuch der Ozeanographie*, Stuttgart, 1911.) where E is the wave energy, L the length, H the height and T the period; g is the acceleration of gravity.
2. BRETSCHNEIDER, C. L.: *Revised Wave Forecasting Relationships*, Proceedings of the Second Conference on Coastal Engineering, 1952. Bretschneider's graph is reproduced in *Shore Protection Planning and Design*, Technical Report No. 4, Beach Erosion Board, Corps of Engineers, Department of the Army, Washington, D.C., 1954, p. 16.
3. Locations of stations, the wind records of which were consulted, are shown in Fig. 1.
4. KLEIN, WILLIAM H.: *Principal Tracks and Mean Frequencies of Cyclones and Anticyclones in the Northern Hemisphere*, Research Paper No. 40, U.S. Department of Commerce, Washington, D.C., 1957.
5. For a description of procedures in refraction diagram construction, see *Shore Protection Planning and Design*, pp. 31–36.
6. As this procedure is a rather lengthy one, it was not carried out separately for the three wave lengths corresponding to the three wind velocity groups. For each section of the shore a single wave length was used which was the average of the longer waves, those generated by the stronger winds. Since the shorter waves contribute relatively little energy, the error in using the calculated coefficient for them also will be a small one.
7. GUILCHER, A.: *Coastal and Submarine Morphology*, London, 1958, p. 85. Also Krumbein, W. C.: "Geological Aspects of Beach Engineering," *Berkey Volume, Geol. Soc. Amer.*, New York, 1959.
8. A graph showing the breaking depth for waves of different heights and lengths is given in *Shore Protection Planning and Design* p. D–42. The angle between wave and shore for different depths and angles of wave approach may be taken from *Wind Waves at Sea Breakers and Surf*, Publication 602, Hydrographic Office, Washington, D.C., 1947, Table 36, p. 157.
9. Values for Materials Transported Parallel to the Shore appearing in Table 4 are derived by interpolation from data in Table 3, each unit of the transportation index being equated with the movement of 39,500 cu. yds. of material per annum.

10. The author is indebted to Dr. J. D. Bankier, Professor of Mathematics, McMaster University, for effecting the statistical analysis.

RÉSUMÉ

Long Point, une flèche de sable à pointes multiples attachée au littoral nord du Lac Erié, constitue probablement le phénomène d'accumulation littorale le plus spectaculaire de toute la région des Grands-Lacs. Le rythme d'accroissement de la flèche peut être déterminé, en partie par le moyen de documents historiques et en partie par les données presque complètes sur les vents que les postes météoroloqique environments peuvent fournir. Ces conditions sont donc idéales pour une l'énquête sur les modifications littorales causées par les vagues.

L'auteur use d'une méthode quantitative basée exclusivement sur les données d'observation des vents et sur l'étude des cartes hydrographiques. Bien que le degré d'exactitude de cette méthode ne soit évidemment qu' approximatif, elle permet toutefois l'étude des processus littoraux sans l'emploi d'instruments élaborés et coûteux.

Cette méthode s'attache à évaluer l'énergie

de la vague d'un point à l'autre le long du littoral. En déterminant la vélocité, la durée et la portée des vents, l'auteur arrive à calculer l'énergie dont la vague dispose perpendiculairement et parallèlement au rivage. Le travail de la vague peut ensuite être mesuré en fixant la position initiale des contours du fond et en rejoignant les lignes de contours à travers la pointe de la flèche en croissance constante.

Entre les données statistiques telles que le déplacement annuel moyen du littoral, les quantités nettes de matériaux accumulés, le degré de pente vers le large, la somme des changements de volume, vers l'aval, de la partie exposée de la flèche, et la distance en milles depuis le col de la flèche, une corrélation est établie par le moyen d'une équation et peut être exprimée graphiquement. Bien qu'une telle corrélation ne soit qu'approximative, on peut toutefois en tirer un certain nombre de conclusions importantes. De plus, cette corrélation permet d'entrevoir à l'avance les modifications futures du littoral de Long Point.

Cette méthode, une fois perfectionée, pourrait offrir d'excellentes possibilités pour l'étude morphologique des littoraux.

Review Article

CLIMATOLOGY AND THE GEOGRAPHY STUDENT

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PETTERSSEN, S.: *Introduction to Meteorology*, 2nd edition, McGraw-Hill, New York, 1959, 327 pp.
BYERS, H. R.: *General Meteorology*, 3rd edition, McGraw-Hill, New York, 1959, 540 pp.
CRITCHFIELD, H. J.: *General Climatology*, Prentice-Hall, Englewood Cliffs, New Jersey, 1960, 465 pp.
KOEPPE, C. E. and DELONG, G. C.: *Weather and Climate*, McGraw-Hill, New York, 1958, 341 pp.

THE PUBLICATION of four new text-books of meteorology and climatology calls for a loud fanfare of trumpets. During World War II many such books were written in response to the needs of the armed services. After 1945, faced with large stocks of the old books, both publishers and writers rested on their laurels for a time. It was a remarkable time, too, in which the parent science of fundamental meteorology was being to a large extent remade at the hands of a new generation of theoreticians —men like Charney, Phillips, Fjørtoft, Fleagle, Kuo, Starr and Eady. Hence the text-books in use in geography and meteorology departments grew rapidly moribund. Since 1955, however, the standard reference books have been revised by their authors, and several new books have appeared. These works are quite remarkably more quantitative, accurate and convincing than their predecessors.

The books under review in this article fall into two classes. Those by Petterssen and Byers are revisions of earlier meteorological text-books, though the revision is so extensive that they can be properly called new. They are written for the meteorology student rather than the geographer, though Petterssen clearly intends to serve a wider clientèle than Byers. Critchfield and Koeppe and DeLong, by contrast, are clearly writing primarily for the geographer, as the absence of mathematics in the texts makes obvious. These are quite new. The two classes of text-book stand in very marked contrast—a contrast that poses for the geographer the very important question "what kind of climatology do we really need?". Geographical students of climatology outnumber those in meteorology departments by ten to one: so the question has some urgency.

Petterssen and Byers are among the leaders of the meteorological profession, a fact quite obvious from the authority with which they write. Both are professors at the University of Chicago, and both publish their books with McGraw-Hill, whose meteorological list is most distinguished. Petterssen has written a simple introductory account of the basic principles of meteorology considered as atmospheric physics. Mathematics is minimal, but is always present in the background. He treats world climates briefly at the end of the book. Byers, on the other hand, writes for the college major in meteorology, and assumes general physics and calculus in his readers. The book includes excellent material on cloud physics, atmospheric dynamics and the general circulation. The reviewer would judge it the best text at this level. It is, however, far beyond the capacity of the typical geography student for much of the distance.

The other two books, by Critchfield and Koeppe and DeLong, are written at a less sophisticated level. Neither assumes any college mathematics or physics—which negative assumption makes both books readily comprehensible to the geography student. They are clear and simple in presentation, and give a good qualitative account of the present state of meteorological science. World climates are treated later in the books on traditional geographical lines, and both books review many other aspects of climatology of direct interest to geographers and biologists. Altogether the pair make reasonably handsome and well-conceived additions to the shelf already housing well-known books

by Trewartha, Blair and others. The reviewer took mild exception to the extreme naivety of phrase affected by Koeppe and DeLong in places—college students need to be forced to think by reading books in fully adult English. There are also a few irritating inaccuracies in Critchfield; thus on page 55, after describing how the Coriolis force causes an apparent acceleration, he assures us that it has no effect on velocity! But on the whole the technical standard of both books is high.

The real issue, of course, is whether the geographical profession can afford any longer to accept a second-class status for its climatology students. We do this if we are willing to agree that they need only a qualitative, descriptive treatment of the field. Climatology is fundamentally and inescapably a quantitative physical science. Its laws are those of physics, its scope the application of those laws to the more enduring aspects of atmospheric behaviour, and to the physical interactions between land, sea, air and living cover. Above all the language of climatology is mathematical and statistical. Descriptive accounts of world climate based on a firm foundation of physical principle are valid and desirable. Descriptive accounts based on mere common sense are rarely accurate, and often misleading.

It is the reviewer's opinion that the geographer's need for climatology is of two kinds. There is first the need for an accurate statement of what world climate is, will be, and has been. Preferably this account will be much more than statistical: it will present the material in the light of climate's impact on man's health, economic activity and future prospects. The general geographer needs such a climatology as part of the description of the earth as the home of human society. He does not, in general, need to know how the results are derived (though this is always a help). The second need is for climatological specialists who are also geographers rather than meteorologists—for men who can serve, in fact, as the skilled and authoritative interpreters between the two disciplines. World climate deserves analysis in its own right, and is a vital component of the complex that the physical geographer must study.

If this distinction be admitted, the geography curriculum should have courses (and hence text-books) of two sorts. For the general geographer, there is a case for a truly geographical climatology, containing an account of how climate affects man directly and indirectly, and how it is related to other physical distributions. For such a treatment it is just conceivable that a prior training in elementary physics and mathematics is unnecessary. The second type of course presents climatology as a geophysical science, and is intended for specialists in physical geography or climatologists themselves. The reviewer believes that such courses absolutely demand physics to the level of elementary thermodynamics, and mathematics to the level of simple differential equations. Petterssen's book will suit an introductory course of this kind very well. Byers is excellent lateral reading at a more advanced level, and the reviewer would die happy if he thought that within his lifetime the geographical profession should insist on meteorology to such a standard from its climatological specialists.

As climatology is now taught, all too often it fails to reach either of these objectives. It consists, typically, of a qualitative and unsatisfying introduction to elementary meteorology, followed by an account of world climate that does not, in fact, meet the general geographer's needs at all. Very often the subject is taught without overt reference to governing physical laws. Most geography students know, and can often explain, the dry and wet adiabatic cooling rates, and their relation to convectional rainfall; but rarely are they taught the first law of thermodynamics, from which these rates are derived. The danger behind all such qualitative treatments is that one can safely extrapolate *only* if the basic laws are known. Some of the popular theories of climatic change, for example, can be right only if Newton was wrong. Critchfield and Koeppe and DeLong have striven very hard to avoid error, and have done so to the satisfaction of the reviewer. But the fact that their treatments are qualitative and descriptive—deliberately so, to feed a proven market—opens the reader to the danger of false confidence. Reading these books, he is bound to

assume that climatology is fun, and is easy. Actually it is fun—but frustratingly difficult.

Though Mr. Dulles is no longer with us, the case for agonizing reappraisals can still be made. A knowledge of mathematics and elementary physics does more than open the door to climatology; it is almost equally important in the study of geomorphology, cartography and soils. And a knowledge of statistics (presupposing the mathematics) is increasingly important in economic and demographic geography. If our students are to be taught these subjects, presumably we shall have to make room for them by dropping much cherished items from our geography honours curriculum. Even so, it would be a constructive sacrifice—and one that has already been made by geologists, biologists, economists and sociologists. There is no step that would, in the reviewer's belief, contribute more to our reputation abroad, or do more to raise the intellectual standards of the discipline as a whole.

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